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BOMB DAMAGE REPAIR (BDR) DAMAGED PAVEMENT REMOVAL AND CRATER BA--ETC(U)
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BOMB DAMAGE REPAIR (BDR) DAMAGED PAVEMENT REMOVAL AND CRATER BACKFILL EQUIPMENT STUDY

APPLIED ENGINEERING RESOURCES, INC.
SANTA BARBARA, CALIFORNIA

DECEMBER 1976

Final Report: February 1975 to December 1976

Approved for public release; distribution unlimited.

AIR FORCE CIVIL ENGINEERING CENTER
(AIR FORCE SYSTEMS COMMAND)
TYNDALL AIR FORCE BASE
FLORIDA 32401

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Airfield bombing is a conventional denial tactic that an enemy may easily employ with great effectiveness; thereby reducing or eliminating the capability of retaliation by air strike. Rapid Bomb Damage Repair (BDR) is necessary to restore airfields sufficiently to launch and recover retaliatory aircraft. The objective of this contract was to improve the current procedures and equipment utilized by optimizing the results of previous BDR research. The study determined that with modification to the existing equipment and changes in removal of upheaval and backfill procedures that (continued on reverse side)

(Item 20 continued)

a 2-hour repair time is possible. In order to realize the 2-hour repair time, the procedures outlined in AFR 93-2 for repairing 750- and 1000-pound bomb craters require modification with a section added to address the repair of craters generated by 25-pound delayed detonation weapons.

PREFACE

This report was prepared for the Air Force by Applied Engineering Resources, Inc. Santa Barbara, California. Under contract F29601-75-C-0052. The contract was originated by the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico. Responsibility was later transferred to the Air Force Civil Engineering Center, Tyndall Air Force Base, Florida. Test data, films and research information derived from all previous Bomb Damage Recovery research efforts were made available to the contractor for analysis as a basis for the contract study.

Information derived from this study will be utilized by the Air Force Civil Engineering Center in further Bomb Damage Recovery research efforts and in evaluation of AFR 93-2 Disaster Preparedness and Base Recovery Planning equipment and procedures.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This Technical Report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

GENERAL STATEMENT OF BDR PROBLEM

The importance of air superiority in warfare has been well established during the last three to four decades. The most effective way to deny an adversary the use of the air is to prevent him from launching his aircraft at all. This can be achieved by either destroying his aircraft on the ground or by damaging his runways by cratering so that his aircraft cannot take off. The increasing use of hardened facilities makes the first alternative more and more difficult. Consequently, it is increasingly likely that one's runways will be attacked before aircraft can be launched.

The likelihood that runways will be cratered by bombs has spurred interest in Bomb Damage Repair (BDR) or, as designated by NATO, Rapid Runway Repair (RRR). BDR processes endeavor to provide a runway lane 50-feet-wide and 5000-feet-long which can sustain repeated dynamic wheel loads of the aircraft during take offs. This objective is achieved by cleaning up the debris and either spanning or filling up bomb craters and capping or covering them with mats. The current procedure as given in AFR 93-2 uses the latter method.

The AFR 93-2 method, however, nominally requires four hours to repair a typical crater produced by one 750-pound bomb. The crew and construction complement are sized to simultaneously repair three such craters. This repair time is considered undesirably long; the ultimate goal of the Air Force is a repair time of 1 hour.

Complicating the process of BDR planning is the increased usage of small penetrator bombs, either air delivered or ground launched. These small weapons can be delivered in large quantities by a single plane and, with appropriate fusing, develop a series of small camouflet or open craters the entire length of the normal runway.

STUDY OBJECTIVE

A series of studies covering damage prediction and crater repair techniques as well as various other aspects of the BDR problem have been conducted for the Air Force Weapons Laboratory (AFWL) during the last 8 years. These studies, including tests by AFWL at the Tyndall AFB BDR test site, have suggested that upgrading the quality of the repair and reduction of the total repair time can be achieved by improving equipment utilization, augmenting equipment complements, and improving equipment design.

The objective of this study was to produce a reference document to aid BDR research (1) in design of alternate BDR processes, (2) in examining options in selection of additional equipment (possibly redesigned), and (3) to present an aid in estimating the minimum times required for the various BDR tasks as a function of the work quantities resulting from bomb damage.

This reference document can then be used as a guide to possible methods

for reducing BDR times to as little as two hours. Further pursuit of research in problem areas highlighted by the results of the study should also suggest new repair techniques and equipment designs to approach the one-hour time goal.

STUDY APPROACH

The approach used in this study was analytical; no field tests were conducted under this contract. The analytical method consisted of the following steps:

1. Conduct a literature review of bomb crater damage and bomb damage repair concepts, processes, and equipment.
2. Analyze time lapse and movie films of bomb damage processes and equipment.
3. Develop BDR task definitions for the AFR 93-2 process, the United Kingdom repair process, using alternate fill techniques.
4. Analyze the variables in each BDR task affecting time and quality.
5. Optimize the work patterns and vehicle utilization.
6. Evaluate the capabilities of commercial equipment items at the BDR tasks.
7. Evaluate mixes of existing, modified and conceptual equipment for cost and time relationships.
8. Prepare a summarization of findings.

SECTION II

TECHNICAL APPROACH

This section describes the major assumptions and steps of the overall study approach outlined in Section I. The description includes discussion of:

1. The rationale for the methodology used.
2. The assumptions and constraints imposed in order to bound the study.
3. A summary of the prinicipal applicable data found in the literature, films, and equipment manufacturers' data sheets.

METHODOLOGY RATIONALE

The Air Force Statement of Work and Technical Requirements indicated that three 750-pound bomb craters were the baseline bomb damage repair (BDR) task. Later in the study, the alternate problem of thirty 25-pound charges was included to assess the current threat.

On either of these repair tasks, in order to evaluate the performance of given repair vehicle, or of a team of vehicles of different types, it is necessary to calculate the productivity of each vehicle on a task which is (1) defined in terms of the unit operations in each task, and (2) for each operation, defined in detail as to quantity of work to be accomplished, average working distance, work material densities/sizes/characteristics and optimized work patterns.

TASK AND WORK QUANTITY DEFINITION REQUIREMENTS

In order to quantify the basic repair tasks into the necessary detail, the literature review and film analysis concentrated on examining the following repair task problem and repair vehicle parameters:

1. Crater sizes and shapes in various soils and in various runway thicknesses.
2. Crater locations with respect to runway edges.
3. Debris sizes, populations and dispersion from ground zero.
4. Repair task sequences.
5. Equipment working patterns and estimated distances.
6. Size, horsepower, attachments, etc., of AFR 93-2 equipment items.
7. Equipment utilization and traffic density in repair area.

Sections III, IV and V present detailed discussions of how the above-listed data was obtained or developed.

BASIC ASSUMPTIONS AND CONSTRAINTS

To assist in quantifying the repair problem, a number of assumptions and constraints were imposed on the repair variables. These were supplied by the Air Force Civil Engineering Center, or selected by AER and reported to AFCEC for concurrence. The assumptions dealt with the threat, the damage site, the materials encountered, and the debris characteristics as follows:

1. Threat
   a. Three 750-pound bombs, or
   b. Thirty 25-pound charges.
2. Damage Site
   a. Three large open craters located on the ends and in the middle of a 5000-foot-long, 50-foot-wide runway.
   b. Thirty small craters, either open or camouflet-type, located in two rows on each side of the 5000-by-50-foot strip; 333 feet between craters in each row.
   c. Negligible slope and grades on runway.
3. Materials
   a. Twelve-inch, non-reinforced concrete runway consisting of 15-foot square slabs.
   b. Sand or clay base courses and sub-base.
   c. Sandy gravel select fill at base stockpile.
4. Debris
   a. Number of each size of representative concrete pieces.
   b. Distance of each size from ground zero.
   c. Distance of each size from spoil area.
   d. Volume of earth ejecta and distribution around crater area.

Densities and bulking factors for materials are discussed in Section V of this report. Specifics regarding debris are discussed in Sections III and V.

The constraints were selected to eliminate very small and very large equipment items, to establish the repair processes to be examined, and in the case of the AFR 93-2 process, to establish a baseline complement of vehicles. These constraints are described in more detail in those areas of this report where they influence any result of problem quantifications.

LITERATURE AND TEST DATA REVIEW

A basic component of the repair task analysis was a review of background information and supporting data in the literature regarding:

1. Design and testing of BDR concepts, processes, and equipment.
2. Damage prediction and weapons effects.
3. Time lapse movies of BDR tests.

The documents and movies reviewed by AER are listed in the bibliography in Appendix A of this report. A summary of the information from these sources that were most useful in subsequent tasks is presented below.

Design and Testing of BDR Concepts, Processes and Equipment

The bibliography of documents compiled by AER in this area is given in Appendix A. The entries in this Appendix are arranged into five subject areas: BDR procedures, crater capping, crater fill, equipment performance, and flotation and dynamic requirements for aircraft.

This list of documents was reviewed to determine which ones should be obtained and examined in greater detail and analyzed. Several of the reports, marked by asterisks, covered the current BDR process in great detail. These marked reports when coupled with a review of the time lapse films provided the majority of the information on BDR processes and equipment.

AFR 93-2(1) (A-1) provided the current manning, equipment list, and procedure for bomb damage repair within the four-hour criteria to repair three 750-pound bomb craters.

The two documents (A-2) by Hokanson and (A-3) by Hokanson and Rollings reported on the FY 73 and FY 75 BDR tests at Tyndall AFB in Florida. The FY 73 report covers tests of the then-current AFR 93-2 procedure. In addition, several equipment items not specified in AFR 93-2 were tested in the repair effort. Also, 750-pound bomb craters and 25 lb C-4 bomb craters were repaired in this series. The FY 75 report covers tests of the AFR 93-2 procedures and equipment in rain and at night for repairing the 750-pound bomb craters. In addition, the repair of 15 lb., C-4 bomb craters was tested. Both of these reports give equipment usages, work patterns and scheduling data for the two series of tests.

In the area of crater capping, the documents covered primarily various concretes used to cap the repair.

The report by Forrest and Shugar (A-9) examined the effectiveness of utilizing conventional materials and procedures for filling and repairing craters. This report found that uniformily graded select fill with a capping equivalent in stiffness to 6 inches of Portland cement concrete meets the quality requirements for rapidly repairing bomb craters.

The bibliography section on dynamic and flotation requirements for aircraft lists three documents concerned with the interaction of the runway surface and the aircraft. (No specific requirements for repaired surface flatness is contained in AFR 93-2.)

Damage Prediction and Weapons Effects

A base of literature was compiled which covered bomb cratering by conventional explosives on uncovered ground and on concrete covered ground. The resultant bibliography is in Appendix B, categorized by major subject.

This literature was reviewed to determine which publications should be obtained for further analysis. Reports noted by asterisks in the bibliography were studied in detail.

Data, equations, models and other prediction procedures were extracted from these reports and analyzed to establish damage parameters for BDR repair tasks. Section III of this report discusses damage prediction in detail.

Much of the early work on cratering was centered on excavation. The removal or displacement of dirt is necessary in many civil projects; e.g. canal digging, dam building, and such activities as the Plowshare Project. Sandia Corporation, the Army Corps of Engineers and Lawerence Livermore Laboratory have all participated in the use of cratering in civil projects.

Due to the interest in denying the enemy the use of his airfields by bombing, recent research has been directed toward cratering in layered nonhomogeneous systems. Some of the early work specifically on bomb cratering was done by Kvammen, Pichumani, and Dick who investigated pavement

Footnote (1) The reference numbers refer to the bibliographies in Appendices A and B.

cratering; Westline analyzed Kvammen, Pichumani, and Dick's data in a similitude analysis for AFWL. Vesic has done theorectical modeling of the formation of the true crater; Hokanson has modified the Vesic procedure and applied it to airfield cratering.

Much of the significant work in airfield cratering has been under the sponsorship of the AFWL as it was given direction of this research in 1971.

In the area of crater data, the reports by Pichumani, et al, give the broadest data base for craters by bombs on runways. The report by Cassino and Chavez (B-1) gives the effects of penetrating bombs (15 and 45 pounds) on various pavement configurations.

Since the soil properties have a significant effect on crater size, a great deal of effort has been expended in this area. Early work was by Ladany and Whitman. Vesic's static model is an attempt to predict crater parameters by inputting soil characteristics. Hokanson (B-32) modified Vesic's method and applied it to data taken at the Hays, Kansas test site.

Several documents concerned with measuring soil properties are also listed in the bibliography. Finally, there are several miscellaneous reports of a specialized nature.

The bibliography includes only those reports and papers of immediate interest to the problem of bomb damage prediction for runways.

The current state-of-the-art in damage prediction to runways hit by bombs in the 250-to 750-pound class and the small penetrating bombs in the 5-to 25-pound class is represented in six reports. These are:

1. Bomb Crater Damage to Runways, Peter Westline (B-14).
2. Soil Property Effects on Bomb Cratering in Pavement Systems, L.D. Hokanson (B-32).
3. Effect of Pavement Design on Cratering Damage from Penetrating Weapons, Cassino and Chavez (B-1).
4. Tyndall AFB Bomb Damage Repair Field Test Documentation and Analysis, Hokanson (A-2).
5. Field Test of Standard BDR Procedures, Hokanson and Rollings (A-3).
6. Bomb Damage Repair (BDR) Damage Prediction, Brooks et al (B-46).

The bomb damage data in Item No. 5 is well documented, however, some of the data is not realistic as Hokanson points out. Hokanson reports that the craters used in the FY 75 test are smaller than what would be expected because of poor energy coupling in that series.

The Brooks Report (B-46) provided the most complete single data source on results of all the bomb damage tests. In addition, the report presents a practical nomograph-type approach for rapid manual development of damage predictions under different conditions for comparative purposes. This data, however, must be combined with additional analytical derivation of repair work quantities in order to be used in analyzing the repair time problems.

Section III further outlines the results of the literature search on cratering and develops some relationships for predicting bomb damage which are subsequently used to size the various BDR tasks.

Time Lapse Film Review

The time lapse film review is summarized below. Use of specific, detailed data from films is noted where applicable in subsequent sections of this report. This summary material is presented to avoid repetition of comments.

One general comment on many of the films is the lack of equipment detail. Time lapse photography doe not provide cycle times or allow the analysis of single vehicle effeciency. Many of the problems were also noted by Hokanson and were improved in subsequent tests.

General Comments on Test 1-1 (FY 73)

The dozer push-loading concrete chunks into the loader 4-in-1 buckets is inefficient, since the dozer waits for the loader to return. Also, the efficiency of any two-machine operation is at best equal to the lowest efficiency of the two machines and is usually taken as the product of the two efficiencies due to operator coordination, machine alignment requirements, and waiting times.

Example: Dozer operating at 60% efficiency excavating
Loader operating at 80% efficiency hauling
Best efficiency = 60%
Probable efficiency = .60 x .80 = 48%

The 4-in-1 buckets are not suited for handling concrete chunks of the size encountered in this test. Too much time is wasted trying to grasp the chunks for carrying. The 4-in-1 bucket allows the dozing surface to be used to slide the blocks to a spoil area.

Traffic patterns were not defined; thus, severe congestion developed at times. Trucks dumping directly into a crater require a ground spotter to position truck. This spotting (aside from the extra man) has a fixed time in each cycle which approaches 1 minute. This is in addition to a dump time of 1 minute. In the early phases, a wait-to-spot time could be eliminated by temporary stockpiles near the crater, but out of the traffic pattern.

The grader utilized on this test does not have sufficient blade side shift capability to perform well at either spreading or spoiling. An articulated grader could crab and not run front wheels over pile to be spread. Articulation could also reduce the turning circle for better cycle efficiency and better performance at backfilling debris.

Equipment types on hand do not generate enough ground pressure to sufficiently compact fill. The possibility of large debris bridging in the crater is high, subsequent settling of select fill into voids is probable. The use of a crane with skullcracker in a casting technique requires a highly skilled operator to break debris and is not effective.

General Comments on Test 1-2 (FY 73)

The compactor does not produce sufficient force to flatten out upheaved pavement; the pavement thickness was designed to handle multiple passes over compacted base course. The explosively compacted sub-base is probably more dense than the design CBR.

A Gradall used for breakout of concrete applies more force by placing the teeth under the concrete and closing the bucket. This uses the dirt surface

as a fulcrum and is usually more effective than the film technique of pulling by retracting the boom. The lever method also does not tip the machine down.

General Comments on Test 1-3 (FY 73)

The wheeled dozer performs well at clearing the edge. The semi-U blade is especially suited to spoiling/pushing odd-shaped objects. The techniques of backfilling to within about two feet of the surface, breaking the edge from within the crater and then spoiling the breakout debris is quite effective.

General Comments on Test 1-4 (FY 73)

The loaders have a poor bite at the pavement with the bucket teeth. Driver visibility is poor in this bucket mode. The loaders should break more pavement before spoiling the debris. The haul time detracts from the operator's "feel" for breaking and requires repositioning the bucket for each process each cycle.

General Comments on Test 1 (FY 75)

Loaders have good speed approaching the crater lip during debris backfilling, but as the load increases and the grade of the crater lip is reached, this speed slows noticeably. The operation near the lip is unsafe due to varying traction and the sudden surge as the large chunks drop over the lip. Since driver visibility is not good, the operation again requires a ground director.

General Comments on Test 2 (FY 75)

The night films are difficult to analyze due to indistinctness of vehicle actions. Traffic control could probably be improved by use of yellow/orange flashers at traffic route points such as turn-ins, waiting areas or stockpiles. Ground directors or crater NCOIC could use flashlight batons to signal operators. Nightime highway repair crews use large banks of truck-mounted lights to adequately light work areas.

General Comments on Test 3 (FY 75)

The truck waiting with fill should dump the load and be removed from the work area. Trucks could unload with moving-dump technique, which produces a shallower pile for grader to spread from. The loader equipped with forks is effective at breakout of small crater lips.

General Comments on UK Rapid Repair Film

The loader at the stockpile uses only one bucket cycle per truck. This is the ideal ratio, but it requires a bucket-to-truck size relationship. The UK loader produces a short load in its one cycle and does not use its articulation to full advantage in the turns to the truck and stockpile.

SECTION III

DAMAGE PREDICTION AND WEAPONS EFFECTS

This section presents a discussion of available data on bomb crater damage to runways relative to the bomb damage repair tasks. This data, for the large 250-pound to 750-pound bombs and the 5- to 25-pound penetrators, was examined as summarized in Section II.

Several test programs have been conducted in recent years to define the level of damage suffered by runways which are subjected to conventional weapon detonations. These test programs were generally conducted without a standardized method of data collection, particularly towards establishment of bomb damage repair tasks. The existing bomb damage data, including the data in the Brooks Bomb Damage Repair (BDR) Damage Prediction Report, had to be reduced to parameters directly related to work functions of crater repair.

DATA SOURCES

Data on the effects of explosives has been accumulated for many years. Much of this work has been concerned with uses of explosives in mining, civil engineering projects, dam building, excavations and others. This work has contributed to the theory of cratering-- for example, defining the extent of fracture zones, etc. There have also been 11 series of tests performed directly to assess runway bomb damage.

The major tests were conducted at Hays, Kansas; Fort Sumner, New Mexico; Civil Engineering Research Facility (CERF), New Mexico; Tyndall Air Force Base, Florida, and Martin-Marietta, Orlando, Florida. The other tests were conducted at Fort Bragg, North Carolina; Eglin Air Force Base, Florida; and Naval Civil Engineering Laboratory, Port Hueneme, California.

Each of the major series has been reported in the literature (See Appendix B). Table 1 lists the test conditions and report references. The Brooks Damage Prediction Report (B-46) examines all of the test series in detail.

CRATER DATA

All of the test series performed provide weapon, pavement, and subbase data in some form. The major data parameters are shown on Table 2. Figures 1 and 2 define the terms of Table 3.

The general crater dimensions were also available.

TABLE 1. BDR TEST SERIES SUMMARY

LOCATION	NO. OF TEST CASES	SOIL	PAVEMENT	WEAPON SIZE	REFERENCE
Hays, Kansas	79	Clay	8 - 11 in. PCC	5, 15 & 25 lb. MK 81, MK 82 and M117 bombs	B3
Fort Sumner, New Mexico	36	Sand	7 in. PCC	5, 15 and 25 lb	B3
CERF, New Mexico	21	Clay, Sand	8-14 in., various PCC and ACC layers	1.5 lb.	B2
CERF, New Mexico	28	Clay, Sand	8 & 12 in., various PCC, CRCP, FRCP and ACC layers	15 and 45 lb	B1
Tyndall AFB, Florida	7	Clay, Sand	8 in. PCC plus 4 in. ACC	25 lb and M117	A2
Tyndall AFB, Florida	6	Sandy Clay,	8 in. PCC plus 4 in. ACC	15lb and M117	A3
Martin Marietta, Orlando, Florida	5	Sand	12 in. PCC	3.7 and 5 lb.	B46
USNCEL, California	5	Sand	8 in. ACC	MK 81 and MK 82 bombs	B46
Fort Bragg, North Carolina	5	Not Reported	6 in. PCC	40 lb	B46
Eglin AFB, Florida	Unknown, average values reported	Sand	6 in. ACC	M117 bomb	B46
Eglin AFB, Florida	3	Clay,	5 in. ACC	AN-M65A bomb	B46

PCC = Portland Concrete
ACC = Asphaltic Concrete

TABLE 2. WEAPON, PAVEMENT AND SUB-BASE DATA

Data Class	Data Items
Weapon Data	Explosive Weight
	Weapon Weight
	Depth of Burst
Pavement Data	Thickness
	Pavement Type
	Reinforcement
	Joint Type
	Overlayment
Sub-Base Data	Soil Type

Table 3 lists the parameters available for most of the tests. These parameters provide the basis for secondary calculations to determine apparent and true crater volumes and ejecta and fallback volumes. The apparent crater volume was directly measured in only some of the tests. The ejecta and fallback volumes and dispersion were not directly measured in any of the tests.

The values used in this report were then based on data developed from all the test series and presented in Reference B-46 . Table 3 indicates the general crater data parameters directly measured and calculated. Additionally, film scaling was used to verify (approximately) the derived damage data.

TABLE 3. AVAILABLE AND DERIVED CRATER DATA

Apparent Crater	Radius
	Depth
	Volume
True Crater	Radius
	Depth
	Volume
Pavement	Blownout
	Repair Area
	Upheaved Area

DATA SUMMARY

Data was summarized for four basic cases; the burst of 750-pound bombs and 25-pound penetrators in both clay and sand. Tables 4 and 5 give the basic measured data for the four cases. The selected case for the 750-pound bomb was taken as a burst at a depth of 110-120 inches, resulting in an open crater in both clay and sand. Selected 25-pound penetrator bomb data produced a camouflet crater in clay at a depth of burst of 95 inches and an open crater at a depth of burst of 48 inches in sand.

The distribution of the ejecta chunks was assumed as a normal distribution and is given in Tables 6 and 7. The clay and sand cases were roughly the same. This distribution information was used to develop spoiling work quantities, as described in Section V.

Due to the wide range of test parameters on 25-pound bomb tests, a selection was made of typical tests from the data files. There are twenty 25-pound data files:

1. H-60 through H-68
2. F-40 through F-47 (excluding F-45)
3. Tyndall FY 74 tests 1-4.

In these twenty tests, nine were in clay-type sub-bases and eleven were in sandy sub-bases. Pavement thicknesses wer 7, 8 and 12 inches, non-reinforced. Nine craters were standard, six were camouflet with upheavel and five were camouflet with spall effects. Depth of bursts were 34, 48, 68, 71, 95, 103 and 119 inches. The resulting damage was widely varying. To establish a set of work quantities for this study the following tests were selected:

1. Hays 63, 64, and 65. A 95-inch D.O.B. in a clay subsoil under 8-inch concrete produced a camouflet with upheavel. Average characteristics were:

Penetration diameter	8.0 in.
True crater depth	130.7 in.
True crater radius	43.3 in.
True crater volume	209.0 ft^3
Pavement repair area	750.0 ft^2

2. Tyndall 74 Tests. A 48-inch D.O.B. in a sandy subsoil under 12-inch concrete produced a standard crater. Average characteristics noted were:

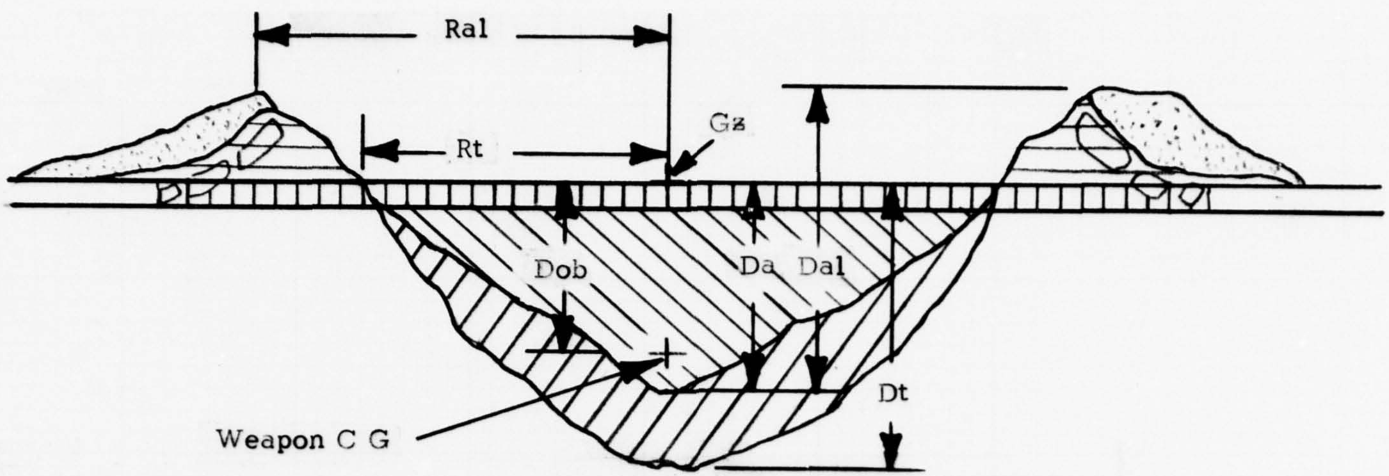
True crater depth	58.2 in.
Apparent crater radius	76.5 in.
Apparent crater volume	215.0 ft^3
Pavement repair area	426.0 ft^2

This data was the basis for a backfill method and an excavate-and-select fill method of small crater repair.

The camouflet mode is considered to have a spherical cavity of the true radius under a cylinder at the penetration diameter. Length of the cylinder is true depth minus twice the true radius.

The standard crater is considered to be a cone with normal fallback debris at the repose angle of the soil.

For the excavation method, an additional 12 inches around the crater outline will be excavated to remove plastically deformed soil for craters from 25-pound or smaller weapons and 24 inches for craters resulting from weapons larger than 25-pounds. Criteria from report by Brooks, (B-46)

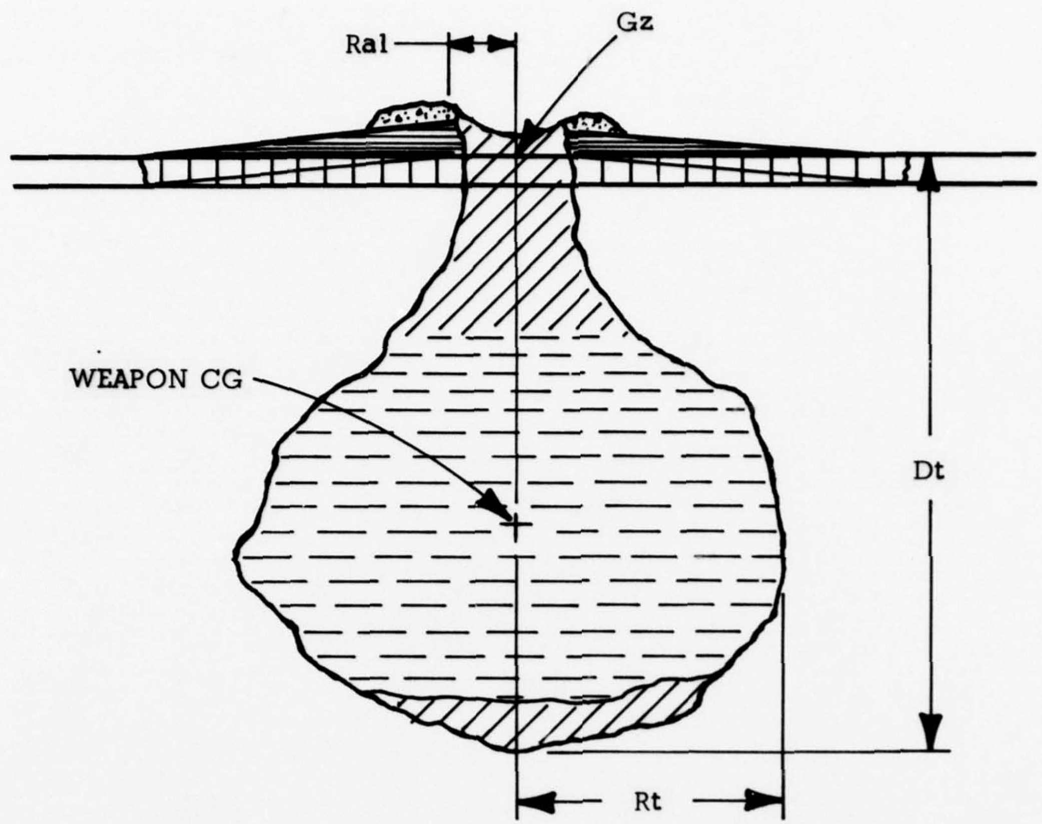


Dt -	True crater depth
Da -	Apparent crater depth, original surface
Dal-	Apparent crater depth, lip
Dob-	Depth of burst
Rt -	True crater radius
Ral -	Apparent crater radius
Gz -	Ground zero
CG -	Center of gravity of weapon

- Fall back volume
- Apparent crater volume
- Ejecta volume
- Pavement repair volume
- Upheaval volume

SOURCE: REFERENCE DERIVED FROM AFWL TR-72-183

Figure 1. Definitions for Open Crater



Dt - TRUE CRATER DEPTH

Rt - TRUE CRATER RADIUS

Gz - GROUND ZERO

Ral - APPARENT CRATER RADIUS

SOURCE: REFERENCE DERIVED FROM AFWL TR-72-183

- FALL BACK VOLUME
- EJECTA VOLUME
- UPHEAVAL VOLUME
- PAVEMENT REPAIR VOLUME
- CAMOUFLET VOLUME

Figure 2. Definitions for Camouflet

TABLE 4. 750-POUND BOMB EFFECT DATA(1)

Parameter	Dimension or Quantity Clay	Sand
Apparent Radius	21 ft	15.6 ft
Apparent Depth	12 ft	9.4 ft
True Radius	21 ft	N/A
True Depth	13 ft	N/A
Pavement Repair Area	3300 ft^2	2268 ft^2
Apparent Crater Volume	254 yd^3	108 yd^3
Depth of Burst	9.2 ft	8 ft
Ejecta and Upheaval	215 yd^3	130.5 yd^3
Excavated Volume	320 yd^3	153 yd^3

TABLE 5. 25-POUND PENETRATOR EFFECT DATA(1)

Parameter	Dimension or Quantity Clay	Sand
Apparent Radius	6 in.	76.5 in.
Apparent Depth	8 in.	44 in.
True Radius	43.3 in.	N/A
True Depth	130.7 in.	58.3 in.
Pavement Repair Area	750 ft^2	426 ft^2
Pavement Blown Out	.7 ft^2	N/A
Apparent Crater Volume	7.7 yd^3	N/A
Depth of Burst	95 in.	48 in.
Excavated Volume	47 yd^3	14 yd^3

(1) *Reference B-7*

TABLE 6. UPHEAVED CONCRETE SIZE DISTRIBUTION
CLAY AND SAND 750-POUND BOMB

Side Length (ft)	Area Per Piece (ft^2)	Total Area (ft^2)	No. of Pieces
1	1	159	159
3	9	396	44
5	25	725	29
7	49	833	17
9	81	729	9
11	121	363	3
13	169	169	1

TABLE 7. UPHEAVED CONCRETE SIZE DISTRIBUTION
CLAY AND SAND 25-POUND PENETRATOR

Side Length (ft)	Area Per Piece (ft^2)	Total Area (ft^2)	No. of Pieces
1	1	21	21
2	4	40	10
3	9	54	6
4	16	64	4
5	25	75	3
6	36	72	2
7	49	49	1

SECTION IV

BOMB DAMAGE REPAIR PROCESS DEFINITIONS

This section provides the general definitions used for analysis of the (1) AFR 93-2, (2) United Kingdom, and (3) alternate fill bomb damage repair processes.

TASK DEFINITIONS

The efforts involved in each of the three BDR processes can be subdivided into some combination of six basic tasks:

Task 1 - Area Cleanup and Crater Backfill with Debris:
This task is comprised of the current method of primary cleanup efforts noted in AFR 93-2; the task involves the pushing of debris into the crater and compacting as necessary. The task does not include the removal of significant amounts of upheaved pavement.

Task 2 - Area Cleanup and Spoiling of Debris:
This task is used if the crater is to be filled with material other than debris; the debris is removed from the crater area and spoiled beyond the planned runway alignment.

Task 3 - Excavation of Fallback and Plastically Deformed Material from the Crater:
This task is undertaken if the settlement of the crater repair is to be rigidly controlled or if the material remaining in the crater is unsuitable as fill.

Task 4 - Removal of All Upheaved Pavement not Removed by Operations in Tasks 1 or 2:
This task completes the removal of all upheaved pavement which no longer meets the roughness criteria; the pavement is lifted, pried up, or otherwise seperated/fragmented from the intact runway.

Task 5 - Hauling and Placing of Select Fill:
This task includes loading, hauling and placement of select fill into the crater, and includes compaction and final grading of the fill.

Task 6 - Cleanup of Small Debris:
This task consists of the cleanup and spoiling of small debris not used as backfill; sweeping is included.

The BDR process as outlined in AFR 93-2, the United Kingdom Rapid Runway Repair (RRR) process and a process utilizing an advanced fill method are made up from combinations of six tasks as shown in Table 8. Note that Task 5, hauling and placing of select fill, for the Advanced Fill Method is not a part of this study. AFCEC has other studies directly related to advanced fill techniques, hence this study examines the repair tasks required before and after an unknown fill technique.

TABLE 8. TASK BREAKDOWN OF BDR PROCESSES

Task	Title	AFR 93-2	UK RRR	Advanced Fill Method
1	Cleanup and Backfill	X		
2	Cleanup and Spoil		X	X
3	Excavate		X	Optional
4	Removed Upheaved Pavement	X	X	X
5	Haul and Place Select Fill	X	X	
6	Cleanup Small Debris	X	X	X
(7)	Advanced Fill Task (Not part of this study)			X

BDR UNIT OPERATIONS

Although the six BDR tasks are the basic functional components of the various BDR processes, each task requires several equipment items, equipment activities, and unit operations. Each task can be broken down into operations such that each operation consists of one type of equipment activity. Table 9 lists the operations making up each of the six BDR tasks.

Each of the BDR unit operations may be undertaken using one or more equipment types. For example, the backfill operation can be done by either loaders or dozers. The work pattern and approach to an activity may vary within an operation depending on the particular equipment type or size chosen. Some of the unit operations, such as spoiling and compacting, appear in several of the BDR tasks. Table 10 lists the unit operations and their characteristics.

To determine the sequence of unit operations in a given process, the earliest possible process start times were established. These earliest commencement times are also listed in Table 10. Thus, the breakdown of tasks into unit operations allows establishment of a relationship in a task to equipment activities so that performance capabilities of the equipment of an operation mix in a task are related to task accomplishment. Equipment is listed which could do the operation; no attempt was made to rate the equipment items by efficiency in this chart.

TABLE 9. BREAKDOWN OF TASKS INTO OPERATIONS

	Tasks	Unit Operations
TASK 1 -	Area Cleanup and Backfill with Debris	Backfill Compact Spoil Debris Clean Sweep
TASK 2 -	Area Cleanup and Spoiling of Debris	Remove Loose Debris Spoil Debris Clean Sweep
TASK 3 -	Excavation of Fallback and Plastically Deformed Material from Crater	Excavate Spoil Debris
TASK 4 -	Removal of All Upheaved Pavement not Removed by Operations in Tasks 1 or 2	Identify slightly upheaved pavement Removed slightly upheaved pavement Spoil Debris
TASK 5 -	Hauling and Placing of Fill	Load Trucks Haul and dump Place fill Compact Grade
TASK 6 -	Cleanup of Small Debris	Clean Spoil Debris Sweep
TASK 7 -	Advanced Fill Process	(Not part of this study)

TABLE 10. BDR OPERATIONS

	Operation	Equipment	Activity	Applications	Earliest Commencement
1.	Backfill	a. Dozer b. Loader	a) Dozes debris into crater with radial passes 360° around crater. b) Dozes as above or loads bucket, lifts debris over lip into crater.	Partial filling of crater.	After crater is selected.
2.	Remove loose debris	a. Excavator b. Backhoe	Fills bucket and dumps outside crater. Prys concrete out of debris.	Remove lip of crater.	After crater is selected.
3.	Excavate	a. Excavator b. Backhoe	Fills bucket and dumps away from crater.	Remove fall-back and plastically deformed material fom crater.	After crater is selected.
4.	Identify slightly upheaved pavement	Level	Locate outer circumferential crack. Measure slope.	Determine pavement to be removed.	As soon as a sector is cleaned enough to examine.
5.	Remove slightly upheaved pavement	a. Dozer b. Loader/bucket c. Loader/forklift d. Excavator e. Backhoe	a, b) Doze and pry up pavement c, d, e) Pry and lift up pavement a, b, c) Work inside or outside of crater, probably best inside d, e) Work outside crater	Remove pavement not meeting minimum slope specifications.	As soon as slightly upheaved pavement is identified in sector. Also after backfill if equipment is to work inside crater.
6.	Spoil debris	a. Dozer b. Loader c. Grader	a, b) Doze debris to spoil area: b) Fills, bucket, dumps at spoil area: c) Pushes debris to spoil area	Remove loose ejecta, excavate, remove slightly upheaved pavement and clean operations.	As soon as material is available in removing, excavation or cleaning operations.
7.	Load trucks	Loader	Fills bucket at stockpile and dumps into truck	Loading select fill.	At commencement of BDR process.
8.	Haul and dump	Dump trucks	Haul and dump	Transport select fill to temporary stockpile or crater. a) building temporary stockpile, b) filling crater directly.	After truck is loaded.
9.	Place select fill	a. Dump trucks b. Dozer c. Loader	a) Dumps and moves forward to spread; b, c) Doze fill from temporary stockpile to crater and spread; c) Loads bucket at temporary stockpile and dumps at crater, then spreads	Fill all of crater to volume of crater remaining after backfill.	After crater is backfilled and compacted or as soon as it is excavated.

TABLE 10. (Continued)

Operation	Equipment	Activity	Applications	Earliest Commencement
10. Compact	a. Vibrating drum b. Pneumatic compactor c. Sheeps foot d. Dozer e. Loader f. Dump truck g. Grader	a,b,c) Drive or are towed at appropriate speed over fill; d,e,f,g) Drive back and forth on fill	Compact backfill and/or compact select fill.	During backfill as needed. During placing of select fill as needed.
11. Grade	Grader	Grades filled crater	Select fill finishing.	After select fill is placed.
12. Clean	a. Grader b. Loader	a) Grades and pushes debris to spoil area, b) Fills bucket or dozes debris to put in spoil area	Mat assembly area. Area of upheaved pavement General runway.	After crater is selected. After backfill or after removal of loose debris. After runway is determined.
13. Sweeper	a. Towed rotary b. Vacuum sweeper c. Rotary wet brush sweeper d. Brooms	a,b,c) Continuous sweeping d) Hand touch up	Mat assembly area, area of upheaved pavement and general runway.	After respective area is cleaned.

SECTION V

BOMB DAMAGE REPAIR WORK QUANTITIES

Repair of the craters and other damage corresponding to the damage predictions of Section III entails the performance of finite quantities of work, regardless of the repair method used. The work quantities vary depending on the repair method used, but are basically defined by damage quantities in terms of the amount of debris (to be backfilled or spoiled); upheaved runway slabs to be removed; cubic feet of fill dirt required; etc.

This section presents the results of a derivation of representative work quantities in each of the BDR tasks for:

1. Large craters
2. Small open craters
3. Small camouflet craters.

LARGE CRATER WORK

The large crater, described in terms of diameter, shape and depth in Section III, results in displaced dirt and concrete which has to be either (a) spoiled, i.e., moved off the runway and discarded, or (b) backfilled into the crater. The large-crater damage prediction closely parallels the data presented by Hokanson and Rollings (Reference A3) on Tyndall test craters. However, one area of particular interest for work quantity definition was not available in any test data-- the debris dispersion.

Debris Dispersion and Haul Distances

Debris dispersion is defined as the number of concrete pieces resulting from the explosion, the size ranges of the debris, and an average throw distance from ground zero for a given size piece. The time and number of dozer trips in spoiling or backfilling tasks is very directly related to the number of pieces and their dispersion. To arrive at a representative dispersion of such debris, the films of the crater area before repair were closely examined. From Hokanson's reported data (A-3) and discussion, scale relationships were developed. These relatonships were applied to the film sequences to obtain an overall envelope of dispersion distances of various piece sizes.

In addition to the concrete pieces, a considerable amount of earth is ejected by the weapon action. Note that a 750-lb. bomb apparent crater of 254 cubic yards (Table 4) has an ejecta and upheaval volume of 215 cubic yards. Since the pavement repair area is 3300 square feet, the concrete is only 122 cubic yards of the ejects/upheaval volume, or 57%. Thus approximately 43% of the debris is earth.

This earth ejecta is usable as backfill material and will be backfilled with the concrete debris in the AFR 93-2 mehtod. For the select fill method, the earth volume is spoiled as an integral part of each dozer spoiling for the concrete pieces.

The implanted charges used in the tests resulted in fairly symmetrical craters and debris patterns. Based on film review, a normal distribution of sizes of debris was established; applying a plus-and-minus 2σ distribution to the reported pavement repair area resulted in a family of debris ranging in size from 1 foot square to 13 feet square and a mean piece size of 7 feet square. As a means of identifying discrete sizes for computer analyses and throw distance estimates, the sizes were called out in a 3σ distribution. (Figure 3; mean size equals 7 feet, $+1\sigma$ equals 9 feet, -1σ equals 5 feet, etc.) This was then developed into a size and throw population distribution as in Figure 4 and Table 11. This data appears consistent with the analysis of the films. Since the large crater was assessed for the case of a 12-inch-thick runway, the area and weight of each piece is then also known in Table 11.

These concrete pieces are displaced by the blast distances from ground zero as far as 125 feet. As expected, the larger pieces are generally found near the crater rim; the smallest pieces (i.e., 1 foot square) at the farthest distance. For work-quantity derivation, it was assumed that even if a large slab of concrete was blown some distance form the crater, the impact of landing would reduce it to pieces 7-feet square or smaller. This assumption is also generally supported by review of the films.

The distances to backfill noted on Table 11 were calculated from the mean distance for a given debris size range to 5 feet past the crater rim. This resulted in a maximum backfill distance of 65 feet. To analyze the spoiling task, it was assumed that spoil areas would be established at a maximum distance of 60 feet from the crater rim, which is based on consideration of runway width and work patterns.

The 1 foot-square pieces were not included in the backfill task since the time required to collect and spoil (or backfill) them is not commensurate with the 4.7 percent of the total concrete volume that these pieces represent. Instead the smaller pieces were allocated to the BDR "cleanup" tasks. Concrete piece size and quantity data is summarized in Table 12. The dispersion pattern is shown in Figure 4.

Backfill Quantities

The crater volume, as provided by damage prediction, represents a volume that requires fill. However, the volume of the fill (i.e., work quantity) depends on the repair method used. Backfilling the crater with debris requires the least select fill material to be hauled to the repair area.

The irregularly shaped concrete pieces, of varying sizes, do not nest well. Numerous voids can be produced when the larger chunks bridge on each other or against the crater wall. This presents a problem to the BDR team OIC, since any backfill operation must be closely monitored to avoid overfilling and/or protuding debris corners. Therefore, a bulking factor of 1.6 (see Table 13) was selected as representative of fractured concrete dozed into a conical pit.

The volume of soil ejected by the explosion can be easily backfilled, since a large portion of it is at the craterlip. As concrete debris is backfilled by a dozer (or loader operating as a dozer), the earth is pushed into the crater

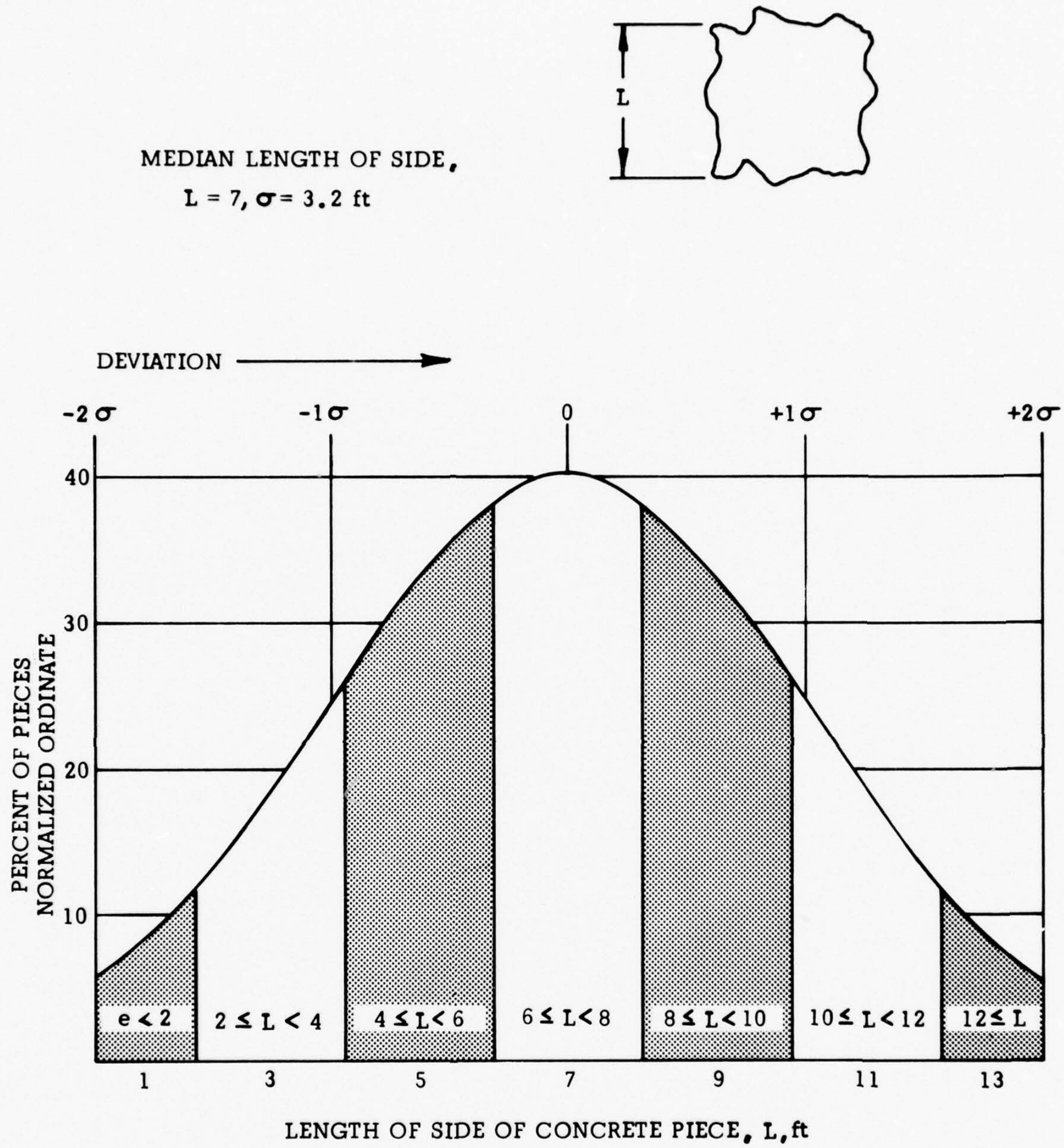


Figure 3. Large Crater Concrete Piece Size Distribution.

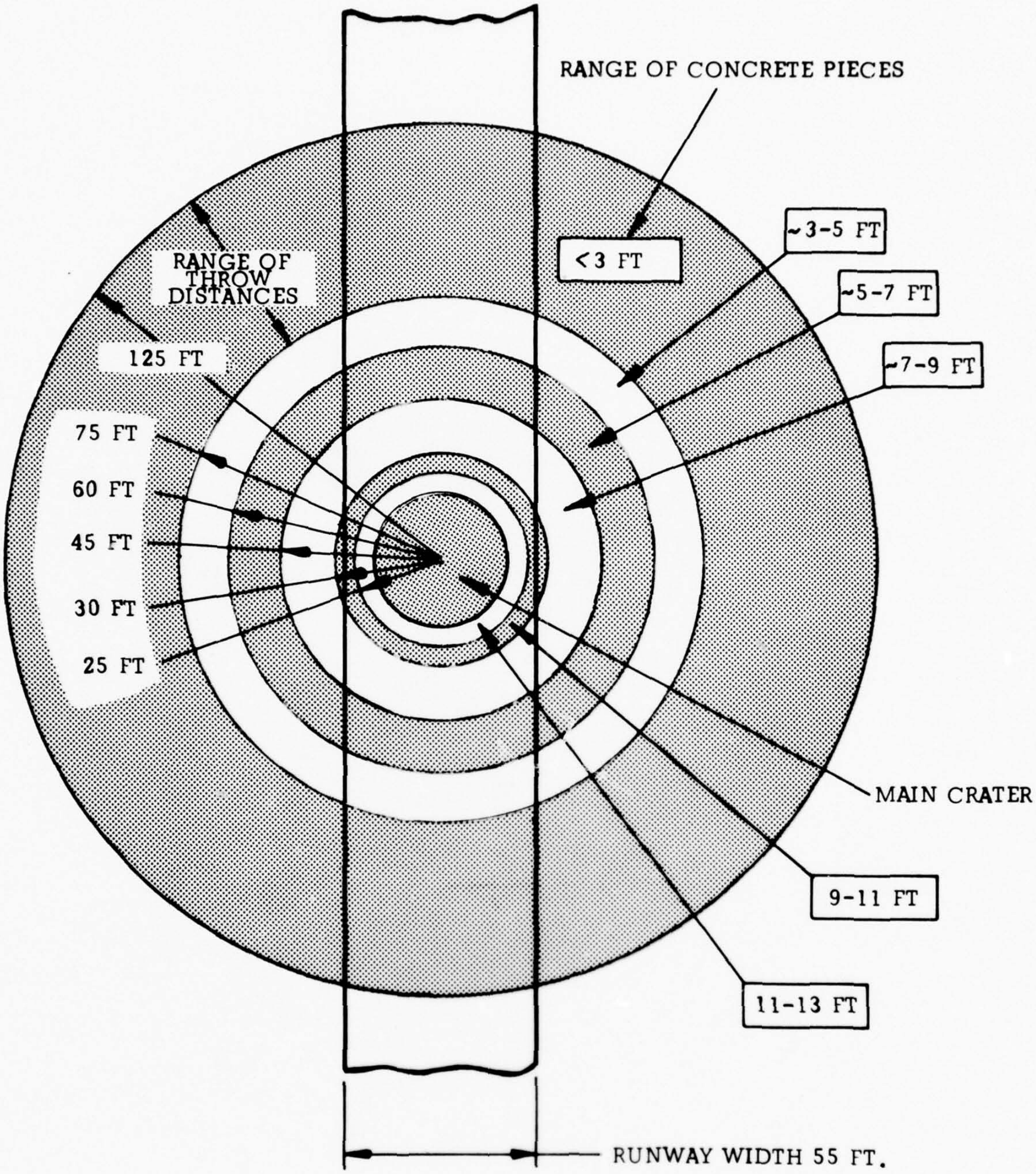


Figure 4. Large Crater Debris Dispersion

TABLE 11. LARGE CRATER CONCRETE PIECE SIZE THROW DISTANCE

Side Length (ft)	No. of Pieces	Area (sq. ft.)	Weight ea. (lbs)[a]	Minimum Throw Distance (ft)[b]	Percent of Total Volume	Spoil Distance (ft)	Backfill Distance (ft)
1	159	1	140	125	4.7	20	N/A
3	44	9	1,260	75	11.7	20	65
5	29	25	3,500	60	21.5	20	45
7	17	49	6,860	45	24.7	35	30
9	9	81	11,340	30	21.6	50	15
11	3	121	16,940	25	10.8	55	10
13	1	169	23,660	20	5.0	60	5
Totals:	262	3,374			100.0%		

(a) Weight for 12-in.-thick concrete, 140 lb/cu. ft.

(b) Distance from ground zero

TABLE 12. LARGE CRATER CONCRETE PIECE SIZE QUANTITIES

Side Length (ft)	Area Per Piece (ft^2)[a]	Limits (ft)	Corresponding σ - Values[b]	Normal Area[c]	Actual Area (ft^2)	No. of Pieces
1	1	0, 2	-2.19 -1.56	.0594	159	159
3	9	2, 4	-1.56 - .94	.1142	400	44
5	25	4, 6	- .94 - .31	.2047	716	29
7	49	6, 8	- .31 .31	.2434	852	17
9	81	8, 10	.31 .94	.2047	716	9
11	121	10,12	.94 1.56	.1142	400	3
13	169	12,14	1.56 2.19	.0594	159	1

a) Rounded Average
b) -2σ to $+2\sigma$ values reference Figure 3
c) percent area represented by normal distribution interval

TABLE 13. BDR MATERIAL PARAMETERS

Parameter[a]	Material		
	Sand	Clay	Concrete
Loose Density	117 lb/ft^3	85 lb/ft^3	88 lb/ft^3
In-Situ Density	135 lb/ft^3	110 lb/ft^3	140 lb/ft^3
Angle of Repose	23 deg.	20 deg.	40 deg.
PHI (Friction)	28 deg.	10.5 deg.	45 deg.
Cohesion	21.6 lb/ft^2	122 lb/ft^2	0
Bulking Factor	1.15	1.30	1.60

(a) Per references A11 and A15, and as adjusted per discussions with USAF personnel.

The United Kingdom (UK) repair method requires more work in hauling fill, since all debris is spoiled and plastically-deformed soil is excavated from the crater, creating a larger hole.

The repair method using advanced fill techniques is not assessed here for select fill tasks, since the actual fill is not part of the AER study.

The in-place volumes of select fill required for a single large crater for each of the two methods using select fill are as follows:

1. AFR 93-2 Method: 4130 cu. ft.
2. UK Method (excavated): 8650 cu. ft.

These quantities; developed from Table 4 and backfilling to within 12 inches of the top are expanded by a bulking factor of 1.5 for the select fill, represent the haul volumes required for each method. The haul volumes are supplied by the truck-loader teams, hauling fom a base stockpile. This bulking factor is typical for the types of select fills discussed with USAF personnel or noted in documents reviewed. The select fill is either dumped in convenient temporary stockpiles near the crater or, in certain circumstances, direct-dumped into the crater.

Compaction Passes

In order to develop a sound sub-base for any capping operation or for a firm earth runway surface, the compaction effort varied with the repair method. The crater area, shape and the loose volume of select fill are indicative of the compaction work quantity. Typical compaction efforts, set at a minimum to afford an "adequate" density, as discussed in AFR 93-2, are as follows:

1. AFR 93-2 Method: 2 coverages
2. UK Method: In-process 2 coverages

Section VII presents a more detailed discussion of the variation of compaction results as a function of equipment used and fill conditions. The grading effort required to produce a smooth surface is easily accomplished with 2 passes of the conventional 12-foot grader blade if the compacted density is high enough. On a non-interfering basis, the grader can level the fill area after the compactor completes its passes in one direction.

Runway Cleaning and Sweeping

The graders have another task -- clearing small debris and rubble. This has to be accomplished in three areas:

1. The runway or shoulder strip used as a haul road by the truck teams;
2. The mat assembly area (when required);
3. The repaired runway surface.

The final vehicle task assigned is the sweeping to remove dust and foreign objects not removed by the other tasks. This is a necessary task to prevent ingestion of FOD by the jet engine of the aircraft. The sweepers cover the entire repaired runway, 5000 feet by 54 feet (270,000 square feet).

SMALL CRATER WORK

Two sets of work quantities are represented for small craters:

1. Work for open craters
2. Work for camouflet-type craters.

The small, open crater represents a scaled-down model of the larger crater previously described. The work quantity analysis used the same approach shown for the large crater. The resulting debris size population and dispersion data is listed in Table 14 for the open mode. The table also lists the backfill distance, an average of 15 feet, and the spoil distance, and average of 40 feet.

The small crater volumes in the open mode are given in Section III. The select fill haul volumes required to fill the crater in the two BDR methods which use a defined select fill are:

1.	AFR 93-2 Method:	20 yd.^{3}
2.	UK Method:	32 yd.^{3}

The camouflet crater is a basically different shape (see Section III); hence, different work quantities are involved. The camouflet crater select fill haul volumes for each of the two BDR methods analyzed for fill tasks are:

1.	AFR 93-2 Method:	3.4 yd^3
2.	UK Method:	33.0 yd^3

Both small crater modes require compaction, grading and sweeping. Compaction efforts required are 2 coverages for each crater mode. These small craters do not provide access for any significant compaction until the fill is completed.

The grading and sweeping work quantities required are the same as for the large open crater since the entire runway must be level and clean when the repair is completed.

TABLE 14. SMALL OPEN CRATER CONCRETE PIECE SIZE THROW DISTANCE

Side Length (ft)	No. of Pieces	Area (sq. ft.)	Weight ea. (lbs) (a)	Minimum Throw Distance (ft)	Percent of Total Volume	Spoil Distance (ft)	Backfill Distance (ft)
1	21	1	140	15	5.6	40	15
2	10	4	560	8	10.6	40	15
3	6	9	1,260	5	14.4	40	15
4	4	16	2,240	2.5	17.1	40	15
5	3	25	3,500	-	20.0	40	15
6	2	36	5,040	-	19.2	40	15
7	1	49	6,860	-	13.1	40	15
Totals:	47	375			100.0		

(a)Weight for 12-in.-thick concrete, 140 lb/cu. ft.

SECTION VI

BOMB DAMAGE REPAIR WORK PATTERNS

The bomb damaged runway area and crater volumes discussed in Section III were related in Section V to specific work quantities in each of several repair tasks. The vehicle routes and techniques used to accomplish these tasks are called work patterns and are discussed in detail in this section.

Work patterns of particular interest in defining rapid and optimum BDR are the cyclical operations a machine performs at a task, including the following typical operations:

1. Approach to material
2. Loading/contacting the material
3. Lifting/pushing/accelerating the material
4. Hauling (pushing) the material
5. Dumping/releasing the material
6. Haul and return over fixed routes
7. Other fixed times, either operating or waiting.

The figures in this section resolve the major BDR tasks into optimum minimum-time work patterns for the various applicable vehicles for a task. "Optimum minimum-time" patterns were chosen that were consistent with patterns used in commercial construction and that were generally the minimum distance, minimum maneuver, minimum nonproductive time cycles.

The work patterns described in this section are the baseline maneuvers that are used to develop time tradeoffs for the total BDR tasks in Section VIII, as well as the analysis of equipment suitability in Section VII. Fixed quantities used in subsequent analyses are also documented.

SPOILING OR BACKFILLING DEBRIS

In Figure 5a, the work pattern for backfilling debris is examined. For this type of backfilling, either the rubber-tired (RT) or tracked (T) dozer can be used. The crater lip and nearby area will be upheaved and required further breaking, so any track grouser damage will not create additional work. Loaders which have the four-in-one bucket can be used effectively on the smaller blocks, about 8 feet square and smaller, by using the dozer mode of the bucket and pushing blocks to the spoil area. In this study, loaders operating as dozers are classed as RT dozers.

In Figure 5b, spoiling debris is illustrated for the two alternative dozers. The tracked dozer requires two additional gear shifts to operate in its shuttle pattern over the more continuous forward pattern of the RT. Crawler tractor gear shifts require an average of 0.1 minute between forward and reverse, which adds 12 seconds to each cycle time.

Figure 5c analyzes a two-machine work pattern which involves spoiling debris by pushing blocks into a loader with a four-in-one bucket which then hauls and dumps the spoil. This pattern is limited in ultimate efficiency (1) by two-machine interdependence, which implicitly denotes waiting times, and (2) by the piece-size limit imposed by the loader's bucket size and lift/travel

a. Dozer Backfilling Crater
   1. Approach and contact
   2. Continue forward as block shifts on blade
   3. Push up and over lip to deposit block in crater
   4. After stop and gear shift at (3), reverse to next alignment
   5. After stop and gear shift to appropriate forward gear, approach for new contact

b. Dozer Spoiling Debris
   1. Approach and contact
   2. Continue forward as block shifts on blade
   3. Increase speed and continue to spoil area
   4. After stop and gear shift at (3), reverse to next alignment
   5. After stop and gear shift to forward, approach for new contact
   4(R). Depositing block in spoil area during a continuous turn, a rubber-tired dozer increases speed and returns to next alignment

c. Dozer Pushing Blocks into Loader Bucket
   1D. Dozer approaches block and makes contact
   2D. Dozer pushes block to lip and waits
   1L. Loader approaches block
   2L. Loader lowers bucket and waits
   3 . Dozer pushes block into bucket
   4L. Loader raises bucket and reverses away from crater
   4D. Dozer reverses from crater lip, stops and shifts to forward
   5L. Loader hauls block to spoil area, stops and dumps
   6L. Loader returns to crater area

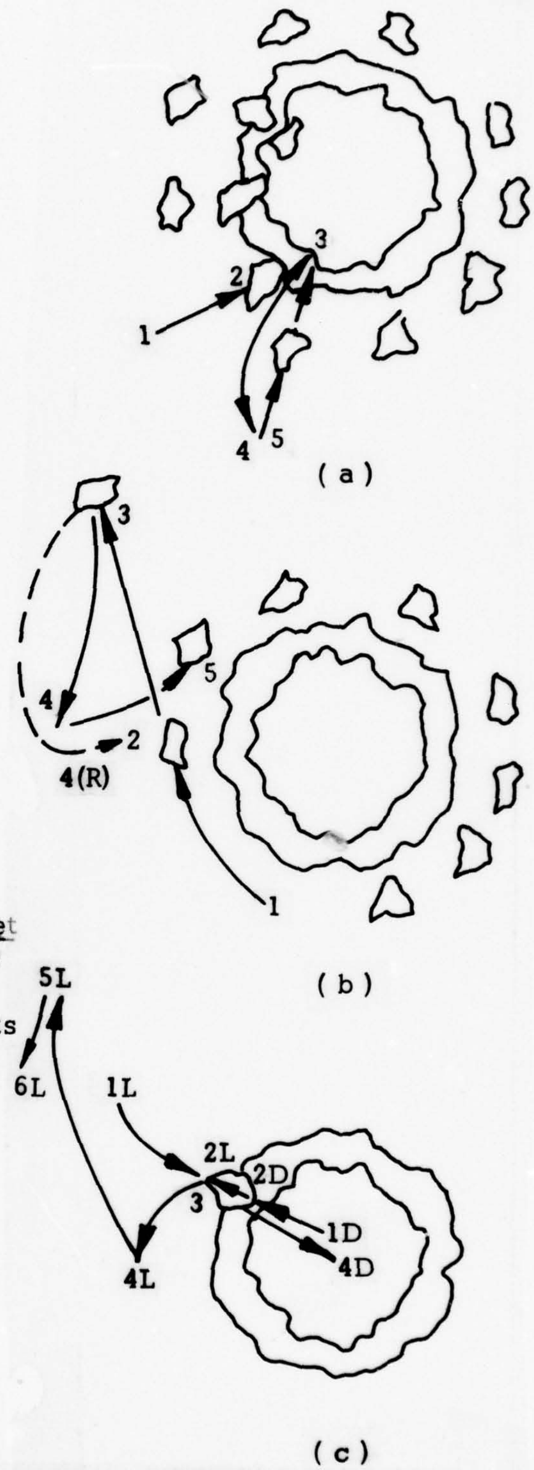


Figure 5. Work Patterns for Spoiling or Backfilling Debris

weight limits.

In addition to the work pattern illustrated in Figure 5, there is the associated work within the crater. This additional work consists of moving the blocks around and compacting as much as possible by the vehicle weight. Tracked dozers can negotiate the sliding, tilting blocks rather well and aid in distributing the backfill more efficiently. Tracked dozers, however, produce low ground pressure and generally do not effectively compact.

Rubber-tired (RT) dozers have ground pressures on the order of 60-80 psi, and with their greater working weight, compact better. RT dozers are, however, subject to changes in traction in the debris and appear in film reviews to be somewhat unsafe. In addition, time is lost when a wheel drops in a crevice and the RT dozer is stuck.

Since this section analyzes work patterns rather than results, the efficiency of vehicles is not quantified. Section VII evaluates the vehicles at each specific task as well as the compaction as by-product of the task.

BREAKING CRATER LIP AND UPHEAVED PAVEMENT

Figure 6 analyzes a work pattern for crater lip breakout from the crater side by a tracked dozer. This approach offers two advantages:

1. It provides a diagonal force to the upheaved concrete, thus improving the lift-thrust vector as well as attacking the weakest failure mode of concrete.
2. The tracked vehicle is better suited to work in and near the crater.

A reverse pattern which pushes the lip into the crater should employ a dozer equipped with a pitch control on the dozer blade to generate a downward cutting force through the ejecta and upheaved concrete. In this function it is imperative to break the entire lip and clear the surface peripheral to the crater. This allows a closer examination for cracked and upheaved pavement which must be removed.

Removal of upheaved pavement away from the crater lip has also been effectively accomplished by loaders with fork attachments. This work pattern is also illustrated in Figure 6. In this pattern, the loader moves forward while lifting to develop the necessary diagonal shear stress on the concrete.

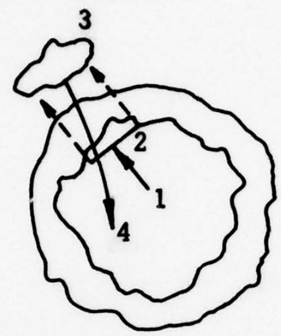
LOADING, HAULING AND PLACING SELECT FILL

Figure 7 illustrates various loader/truck work patterns in the task of emplacing select fill in the crater.

A bucket loader establishes a repetitive cycle at a stockpile (or borrow pit). With slight variations, it can work at efficiencies approaching 80 percent for periods of time up to about one hour. The number of trucks it can load during that hour is not solely dependent upon the cycle time. One important constraint is the relationship of bucket size to dump truck size. Figure 8 from "Evaluation of Integrated Engineer Equipment Systems," AD 480 342L, illustrates a 2 1/2 cubic yard bucket loading about 6700 pounds of sand per cycle. This is short of a full load for a 5-ton truck, so the loader either puts another full bucket in the truck, which overloads it, or puts a partial bucket in the truck. In the United Kingdom film, the loader made one cycle and the truck left with a short load.

d. Dozer Breaking out Crater Lip

1. Dozer approaches and makes contact
2. Developing more force and manipulating blade for best bite, dozer starts breakage
3. Dozer pushes breakout load beyond lip, stops and shifts to reverse
4. Dozer reverses into semi-filled crater, stops and shifts to forward gear



e. Loader Breaking out Upheaved Pavement with Fork Attachments

1. Loader aligns forks to area to be removed
2. Loader drives forks under pavement
3. Loader raises forks and moves forward, stops and shifts to reverse gear
4. Loader reverses for new cycle, stops and shifts to forward

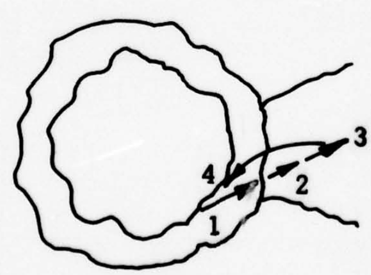


Figure 6. Work Patterns for Upheaval Pavement Removal

From the referenced study, a 5-ton truck is best matched to a 3 1/2 cubic yard bucket loader. This provides a full load in one cycle. Since trucks in queue can move into position for loading while the loader is filling the bucket, one truck can be loaded for each loader cycle.

When a loaded truck arrives at the crater area, it can dump directly into the crater or in a temporary stockpile. Direct dumping is shown in Figure 7g and h. Dumping over the crater edge (Figure 7) is often required to provide material to fill voids left by backfilling with large debris pieces. This is especially apparent in the small-crater test films. Reverse dumping requires additional time in a work cycle to spot the truck. A ground observer (spotter) is advantageous to select the dump area and coach the driver to the crater edge.

Figure 7 analyzes a drive-through dump technique useable when the crater is nearly full. This method is suited for the last 6 inches or so of fill. It produces a spread-out lift which can be more easily leveled and, in addition, compacts the fill area due to the truck traffic. The technique does not require spotting and reverse gear operations, but it does require adequate load-bearing capacity in the built-up fill so that the truck does not bog down and require assistance.

GRADING AND COMPACTING THE FILL AREA

Figure 9 is analyzed for a grader work pattern; however, self-propelled compactors would generally use the same pattern.

A problem with the grader is a lack of mobility in the crater area until the fill nears the pavement surface. Leveling of dumped fill in the lower depths must be accomplished by the dozers, and later by loaders.

Compaction is a complex problem on any earthwork project. (The trade-offs in compaction effort are discussed in detail in Section VII. This section only discusses work patterns.)

FIXED CYCLE TIMES AND CONSTANTS

Because the work patterns developed in this phase of the study provided a basis for evaluation of specific equipment items, each task was analyzed for cycle times. The work accomplished per cycle and the total amount of work in that task were then compared to develop ideal task times. The application of equipment, operator and job efficiency factors allow a valid prediction of total process times for different processes and different equipment mixes.

The major several factors that were developed for the equipment analysis are shown in Table 15, BDR Constants. The table lists the fixed times, friction coefficients and efficiencies used in the subsequent analysis.

TABLE 15. BDR CONSTANTS

FIXED TIMES

Dozer shift, forward-reverse	0.1 minutes
Dozer approach, breakout/digging	0.5
Bucket loader, stockpile cycle	0.4
Truck spotting at crater	0.6

TABLE 15. BDR CONSTANTS (Continued)

Truck dumping	1.0 minutes
Grader spreading	0.5
FRICTION COEFFICIENTS	
Rubber on dirt	0.6
Rubber on concrete	0.71
Track on dirt	0.75
Track on concrete	0.5
Concrete on concrete	0.5
Concrete in loose dirt	0.7
EFFICIENCIES	
Mechanical	
Tracked dozers	0.65
Wheeled dozers	0.70
Trucks	0.80
Loaders	0.70
Graders	0.70
Compactors	0.75
Operator	
Daylight	0.85
Night or Rain	0.70
Job (Management)	
Day	0.85
Night	0.75

These factors do not prejudice one equipment item against another since they are applied equally to each work pattern. The fixed times and friction coefficients are based on data in References A-11 and A-15, a review of the time lapse films, and observations on commercial construction sites. These factors and the equipment efficiencies are refined further to reflect as closely as possible these factors as they exist in an Air Force BDR unit.

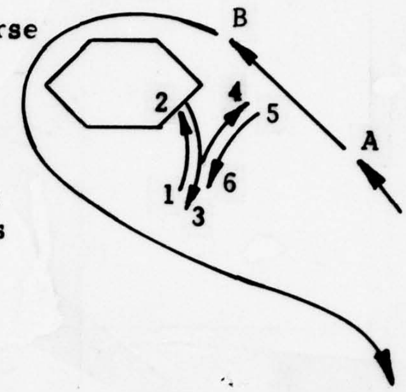
The next section collects the damage factors, work quantities and work patterns and evaluates individual machines performing individual BDR tasks in the three different sequences.

f. Bucket Loader Loading Trucks With Select Fill

1. Loader turns into stockpile, dropping bucket during approach, thus "driving" the bucket to overflow, whereupon it stops
2. Loader raises bucket while shifting into reverse
3. Loader reverses minimum distance to allow turn to waiting truck
4. Loader with raised bucket drives to truck
5. Loader dumps into truck
6. Loader shifts to reverse and backs away from truck in a Y-turn, shifts to forward and starts next cycle

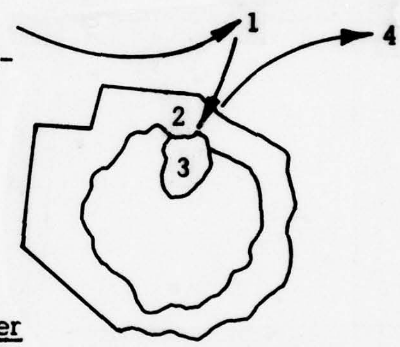
A. Trucks queue at point A, move to point B for loading

B. Trucks leave loading spot in a traffic pattern away from loader and arriving trucks



g. Trucks Direct-Dumping in Crater

1. Truck approaches work area, turns for alignment, stops and shifts to reverse
2. Truck backs to crater edge, under spotter control
3. Truck raises box and dumps
4. Truck leaves crater area in a coordinated traffic pattern, dropping box on the move



h. Trucks Dumping on Move in Nearly-Filled Crater

1. Truck approaches crater which is sufficiently filled and compacted to allow truck mobility and stops
2. Truck raises box, trips dump gate and spreads load on move through fill area
3. Truck leaves fill area

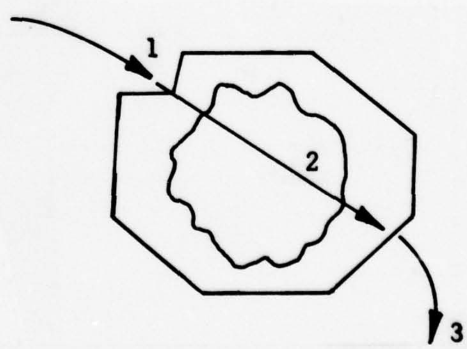


Figure 7. Work Patterns for Handling Select Fill

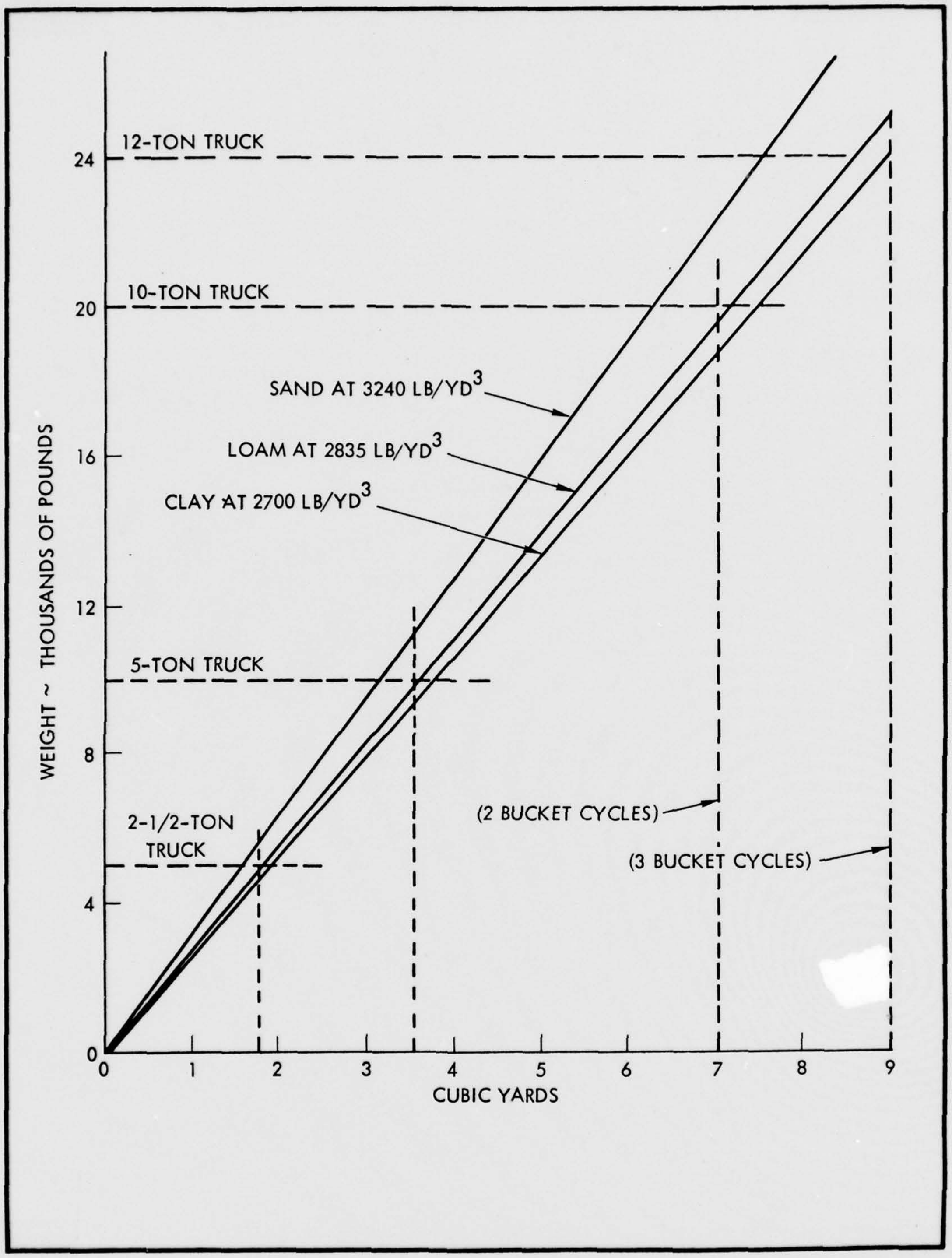


Figure 8. Bucket Size Relationships

i. Grader Spreading in Nearly - Filled Crater

1. Grader sets blade height above ground to optimum lift depth for type of select fill, spreads through work area, stops and shifts to reverse
2. Grader reverses to starting point, stops and shifts to forward
3. Grader turns to new line af attack and next blade width of material

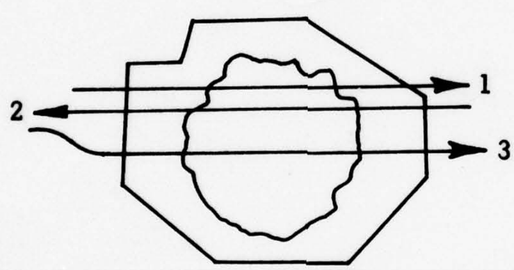


Figure 9. Work Patterns for Grading and Compacting

SECTION VII

EQUIPMENT EVALUATIONS

Once the work patterns and work quantities are established, the speed and productivity of a machine can be estimated for each task it can perform. This section summarizes this evaluation of individual equipment item performance on the BDR tasks. Equipment which had capabilities in BDR were selected from a comprehensive range of sizes. Equipment evaluated, in at least a preliminary way, included items from major U.S. manufacturers. Minor and major modifications were also considered; these are discussed in more detail in Section IX. Where there was no clear-cut advantage to a small size or a particular piece of equipment, the list was reduced and the larger and also the most typical machines were assessed for performance at both large and small crater repairs.

COMPUTER EVALUATION APPROACH

In some repetitive tasks, where several variables were involved, a time-sharing computer program was used to evaluate several equipment candidates. Specifically, programs were written to cover three tasks:

1. Dozer Backfilling debris
2. Dozer spoiling debris
3. Truck teams hauling fill

The program listings and lists of symbols appear in Appendix C of this report. This section describes the variables and constraints used in the analysis and discusses the results for the evaluated vehicles.

The programs were written in Extended Basic Language for ease of programming and clarity of instruction listings. The only inconvenience in reading the program is the language restriction to two alpha-numeric characters for any parameter designator. This results in some designators not being the common abbreviation for the engineering unit.

SPOILING DEBRIS

The program for the dozer spoiling debris calculates from the input data the traction limit of the vehicle on its working surface, dirt or concrete. The drag forces of the vehicle are then calculated, based upon rolling resistance, working grade and load.

The load resistance is calculated in a subroutine which uses the several sizes of debris. An iteration within this subroutine determines the maximum piece size each vehicle can handle, based upon the drag force it adds and the vehicle traction limit. Any limitation is printed out in the results. Vehicles which cannot handle the mean piece size are so noted and are not examined further, since an additional drag force exists due to the soil ejecta in the immediate crater area.

A return to the main program then calculates available rimpull force of the vehicle and determines the maximum horsepower-limited velocity, which can be compared to an input value of either specified maximum velocity

or limited velocities relate to safety in congested areas and to operator ability to maintain load/vehicle control. The task-limited velocity is a more realistic evaluation since at short travel distances few vehicles can reach manufacturers' top speeds. Also, the dozer program used for the evaluation does not contain an acceleration time distance calculation. This added refinement would be useful for longer spoil distances or in earthmoving tasks where the dozer blade is incrementally loaded and a full load accelerated. For BDR evaluation of debris spoiling and dozing at short distances it is an unnecessary complication of the calculations.

Computer runs were made at both velocity limits for this BDR analysis. The resulting variance between times for the tasks will be discussed later in this section.

The times required for each vehicle to push debris to the spoil area and return are calculated and include fixed times for load alignment and gear changes. The total time for all pieces larger than 1-foot square is then summed up for each vehicle.

Eighteen dozers and loaders were evaluated at spoiling debris. These manufacturers and model types are listed in Table 16. This equipment encompasses the complete range of equipment characteristics commercially available as standard and non-modified. Appendix D contains tables of these equipment items and their pertinent characteristics.

Weights, horsepower ratings, and other data were from the 1975 International Specification Index and the manufacturers' brochures. Fixed times, listed in Section VI of this report, were derived from the Caterpillar Performance Handbook, Nichols' Moving the Earth, and actual observations of operating times. All vehicles could handle all sizes of debris on level ground, with times varying from 14 minutes at short spoil distances to 45 minutes at longer distances.

Two representative vehicles were tried on a steep grade task, which is typified by moving debris out of a crater with a 44-degree ramp. A 180-horsepower crawler can handle pieces up to 7-feet square, while a 470-horsepower, rubber-tired dozer can handle pieces to 11-feet square. Both vehicles were working on dry soil at their respective weights of 39,000 pounds and 116,000 pounds. The results that the rubber-tired dozer performed better than the crawler is not indicative of any advantage of tires over tracks, but rather of the differences in horsepower and weight. Since traction is primarily a function of weight and velocity is a function of horsepower, the bigger machines have higher performance.

In addition to time considerations it should be noted that the crawler would not be preferred for spoiling since its tracks may damage undisturbed pavement. However, the crawler can be used at the crater where track damage and travel speed are not primary concerns.

TABLE 16. DOZERS AND LOADERS EVALUATED

Manufacturer	Model	Vehicle Type
Case	W26B	Loader
Caterpillar	814	Rubber-tired (R-T) dozer
Caterpillar	824B	R-T dozer
Caterpillar	834S	R-T dozer
Caterpillar	D7F	Crawler (Tracked)
Caterpillar	D8K	Crawler (Tracked)
Clark	280	R-T dozer
Clark	380	R-T dozer
Eaton	Yale 1700	Loader
Eaton	Yale 4000	Loader
International-Harvester	H560	Loader
International-Harvester	TD-20	Crawler (Tracked)
Steiger	Bearcat	R-T dozer
Steiger	Cougar	R-T dozer
Steiger	Tiger	R-T dozer
Terex	72-71	Loader
Terex	82-20	Crawler (Tracked)

BACKFILLING DEBRIS

The program for backfilling debris was adapted from the dozer spoiling program. Finally, the two programs were merged into one, with the program containing options for either spoil or backfill for both the large and small crater repair tasks. The program combines debris populations, sizes, and distances to calculate backfill and spoil times for large and small craters.

Dozing Evaluations

The eighteen vehicles with dozing capability were then evaluated by the computer program previously described.

The vehicles were assessed once using a task-limit velocity of 440 feet per minute (5 mph) dozing a block with accumulating soil and 880 fpm (10 mph) on the return portion of a spoiling work pattern. These velocities reflect the requirement for added tractive effort in the lower gear ratios on the haul portion and higher return speeds when the vehicle has no load.

To examine the effect of the velocity limitations, another run was made using the manufacturers' specified top speeds. A comparison of the productivity ranking of the vehicles under these two constraints are shown in Table 17. Since the haul speed equations consider tractive effort required versus rated horsepower, the top haul speed is usually constrained by the load. Some vehicles changed rankings under the specifications velocity constraint, indicating that the task-limit return speed was reducing their productivity.

TABLE 17. Ranking of Spoiling Productivity as a Function of Equipment and Velocity. (a)

Vehicle	Task-Limited Velocity	Specified Maximum Velocity
Caterpillar 814	7	10
Caterpillar 824B	12	12
Caterpillar 834S	8	8
Clark 280	10	14
Clark 380	13	16
Steiger Bearcat	1	1
Steiger Tiger	3	2
Caterpillar D7F	16	13
IH TD-20E	15	4
Terex 82-20	14	6
Yale 1700	2	3
Yale 4000	5	5
IH 560	9	9
Terex 72-71	11	15
Case W26B	4	7
Steiger Cougar	6	(b)
Caterpillar D8K	(b)	11

(a) Spoil Distance of 50 feet
(b) Not assessed at both limits

Table 18. lists the times at various spoil distances of the top three dozers candidates for spoiling large crater debris, using the manufacturers' specified top speeds.

TABLE 18. BDR Spoiling Task Times on Large Crater

Spoil Distance (feet) (a)	Time (minutes) Bearcat	Tiger	Yale 1700
20	13.6	14.0	15.3
35	19.8	20.7	23.2
50	24.9	26.3	29.9
55	26.6	28.3	32.2
60	28.0	29.8	33.8

(a) See Section V for debris characteristics at these spoil distances.

By comparison, The slowest vehicles took 17.6 minutes at a 20-foot spoil distance and 45.4 minutes at 60 feet.

Table 19 lists the backfill times at various backfill distances for the top three candidates. Since only one cycle is required by the program for the debris population at a backfill distance of ten feet, the times is misleading. Considerable soil is distributed around the crater, however this close-in soil will be considered as crater lip.

TABLE 19. BDR Backfill Task Times

Backfill Distance (feet) (a)	Large Crater Time (minutes)		
	Bearcat	Tiger	Yale 1700
5	0.6	0.6	0.6
10	0.6	0.6	0.6
15	2.1	2.2	2.2
30	5.8	6.2	6.3
45	13.6	14.5	15.8
65	29.1	31.1	37.1

(a) See Section V for debris characteristics at these backfill distances.

A further analysis of the rankings reveals that the top three vehicles are two dozers and a loader. To provide all-weather capability, a crawler should be retained. The top two crawlers performance at the BDR tasks are listed in Table 20. Two heavier dozers, a D7 and D8 were also evaluated. Since the spoil and backfill tasks did not require large tractive effort, these vehicles ranked lower since their heavier weights caused lower haul speeds. For comparison, at a 60-foot spoil distance, the D8 time was 40.2 minutes

TABLE 20. Crawler Task Times

Distance (feet)		BDR Large Crater Time (minutes)	
Spoil	Backfill	IH TD-20	Terex 82-20
20	-	15.6	15.7
35	-	24.1	24.3
50	-	31.7	31.9
55	-	34.3	34.6
60	-	36.4	36.7
-	5	0.6	0.6
-	10	0.7	0.7
-	15	2.4	2.4
-	30	7.1	7.1
-	45	17.3	17.3
-	65	38.3	38.5

and at a 65-foot backfill its time was 42.4 minutes. The D7 times at these distances were 41.6 and 43.9 minutes, respectively. These small time differences will be compared to cost differences in Section X of this report.

On small craters, a single average distance was used for spoiling. For backfill on a small crater an average distance of 15 feet was used. Table 21 lists the times of the best rubber-tired dozer and tracked dozer at these tasks on a small crater.

TABLE 21. BDR Debris Backfill and Spoiling Time Comparison

	Small Crater R-T Dozer Steiger Bearcat	Tracked Dozer I-H TD-20
Spoil Time (minutes)	11.1	13.7
Backfill Time (minutes)	8.3	9.2

Since the debris population differs between large and small craters (see Section V), direct comparisons between dozer productions on the two sizes of craters are not valid.

FILL LOADING AND HAULING

Another program was written to assess truck and loader teams for the fill loading and hauling task. The truck program contains variables for queue times (set at zero on this study) at the stockpile and at the crater. In addition, when calculating travel times, the program includes a calculation of acceleration time and distance for both the haul (loaded) and empty return portions of a cycle. An added feature of the truck teams program was the ability to compare 5- and 10-ton trucks, as well as 3-and 3 1/2-cubic yard loaders.

The program calculates productivity for a single truck and loader, allowing sensitivity analysis comparisons for the load-haul operations for different distances, loads, and equipment. The total task time for the truck-loader team does not have a job efficiency factor included. To assess the time for a team working at less than 100 percent efficiency, the job factor can be defined and input, and included as a multiplier at Step 3500 (see listing in Appendix C of this report). Applicable characteristics of the 5-and 10-ton trucks, as well as loaders are listed in Appendix D.

The truck team time is calculated in the listing included in Appendix C on a work quantity of 2160 cubic feet of fill volume. This volume represents a rounded volume based upon thirty 5-ton truck loads used on the Tyndall tests for a single large crater. Times for other quantities can be ratioed directly since the distances and payloads remain the same. With a fill quantity of 2160 cubic feet, the five 5-ton trucks and one 3 1/2-cubic yard loader require 27 minutes, while five 10-ton trucks and one 3 1/2-cubic yard loader require 14.9 minutes.

Hokanson and Rollings reported in AFWL-TR-75-148 that the 5-ton truck teams required 94 minutes to deliver 30 loads to the crater area. This was broken down into 83 minutes of loader work, at a mean rate of 2.8 minutes per truck. This is a poor efficiency rate for loaders. An industry-accepted time (Reference A11) for a loader working from a stockpile into a dump truck is 0.4 minute per loader cycle. Even if the loader requires two cycles to fill a 5-ton truck, this should result in a fill time of only 0.8 minute. If the stockpile has been in place for a long time, it may approach bank density which could add 0.04 minute; inconsistent operation can add another 0.04 minute per cycle. Each cycle could approach 0.48 minute, two cycles per truck would take 0.96 minute. This would indicate an operator or job efficiency

of approximately 35 percent existed on the tests.

A computer run was also made to compare 5-ton truck teams loaded by a single 3-cubic yard bucket load cycle against 5-ton trucks loaded by a 3-cubic yard loader which filled the trucks by multiple cycles. Use of the complete fill cycle increased team productivity and decreased the required task time since more material was transported per truck load. Since the time used in the run was 0.4 minute per cycle, the loading time was insignificant compared to the truck cycle time of approximately 6.5 minutes.

Further increases in efficiency can be achieved by using a 3 1/2-cubic yard bucket. This volume weighs 11,000 pounds. This is a reasonable lift for loaders such as the Caterpillar 966 and larger models, or the Clark 125 and larger models. The 3 1/2-cubic yard bucket is suited to a single cycle load in 5-ton trucks and a two cycle load in 10-ton trucks. The 10 percent overload per truck shoule not damage vehicles in good operating conditions.

The loaders evaluated in this test were selected from a large group of available loaders. Only small and medium capacity vehicles were examined, due to the confined working area. All loaders were of articulated frame design to allow maximum optimization of work patterns and all were rubber-tired to provide mobility and speed without an added requirement for equipment haulers.

Although all loaders assessed were satisfactory, the recommended size is a light loader (under 50,000 pounds in weight). This size provides a breakout force of nearly 40,000 pounds; a 15-foot square of 12 inch thick concrete weighs approximately 31,500 pounds. The 3 1/2-cubic yard bucket previously discussed is also recommended. Little differences between manufacturers is found for a given size loader, hence any USAF acquisition should follow the normal competitive procurement procedures and consider sizes applicable to other base engineering tasks. The same policy appears applicable to dump trucks. Selection of a manufacturer can depend on competitive pricing, delivery schedules and availability of service and parts. The performance of various makes of both 5-ton or 10-ton trucks can be equalized by specified sizing of axles, chassis, engine and dump boxes.

The 27 minutes for 2160 cubic feet should be adjusted for the probable job efficiency, e.g. 70 percent. This would result in a task time of 38.6 minutes.

The other BDR equipment items used in other BDR tasks were evaluated by calculating the area or volume handled per cycle or unit operation, summing up the times for a work pattern element, and compiling a total task elapsed time per crater. Efficiency factors were applied for tasks involving many cycles. These evaluations are described in the following paragraphs.

CLEARING HAUL ROAD

During the travel to the damage area in BDR force deployment, the graders and rubber-tired dozers can be used to clear a haul road for the trucks. With the graders using a 12-foot blade set at 30 degree running angles, each grader can clear a 10-foot width. The three graders assigned to BDR can thus clear a 30-foot path of any small rubble that might slash tires and/or cause blowouts. The R-T dozers and loaders can be deployed ahead to spoil

pieces larger than 2-feet square off the haul road path to make the grader work easier. The graders can do overlap clearing (lead vehicle farthest into runway) at a rate of approximately 3 mph; this clearing speed results in a 19-minute time to clear a path the entire length of a 5000-foot runway. This time period is just sufficient to select a crater and clear a path to the crater in time for the first loaded trucks arriving at the crater area.

CRATER LIP REMOVAL

The crater lip is approximately 2-feet high at the crater and tapers down to the pavement at distances to thirty feet. The lip consists of both dirt and concrete ejecta. In the backfill method of AFR 93-2, it is a straightforward task to push this ejecta into the crater; however, the select fill method (UK method) necessitates the removal of this lip.

AFR 93-2 Process

Ideal vehicles to backfill the lip area are the rubber-tired or tracked (crawler) dozers and the loaders equipped with four-in-one buckets. The crawler is very effective at this task, since the pavement is already damaged and further pavement damage from tracks is not a problem. The crawler also can operate more safely on the crater rim. The rubber-tired dozer can develop adequate traction to perform the task; however, it has difficulty in pushing the debris far enough into the crater and reversing out again. The loaders have the same problem as the rubber-tired dozer; in addition, the loader bucket presents a vision blockage and thus increases the chance of the vehicle becoming "stuck" in the partially-filled crater.

The repair-problem crater has a circumference of 130 feet; a 12-foot dozer blade thus requires 12 radial cuts to backfill the lip. The material left on the pavement by this technique will be distributed by the remaining spoiling/backfilling cycles. A time per pass at this task will approximate 1 minute, with each cycle requiring two direction changes and a cautious approach to the rim.

UK Process

For the select fill (UK) method, the dozers should work tangentially (Figure 10) to the rim, which presents more of a problem. Now the travel time to spoil the lip material will add 1 minute to the time per cut. The number of cuts will reduce to about fourteen with a 12-foot blade, but now windrows are left by the outer edge of the blade. A semi-U shaped blade reduces this drift of material off the surface. In addition, since the crater's upheaved pavement includes radial cracks, this technique is slow because the blade cutting edge must be kept above the upheaved pavement which is covered by the ejecta. This method requires 28 minutes for one dozer to perform lip removal.

An interesting alternate to dozing the lip for the select fill method is the use of an excavator. The excavator recommended for such BDR tasks is a rubber-tired vehicle, but larger than most commercial backhoes. To allow maximum use of such a vehicle on large debris, the excavator should be in the 15- to 20-ton class. (The size recommendation is developed under removing upheaved pavement in this section).

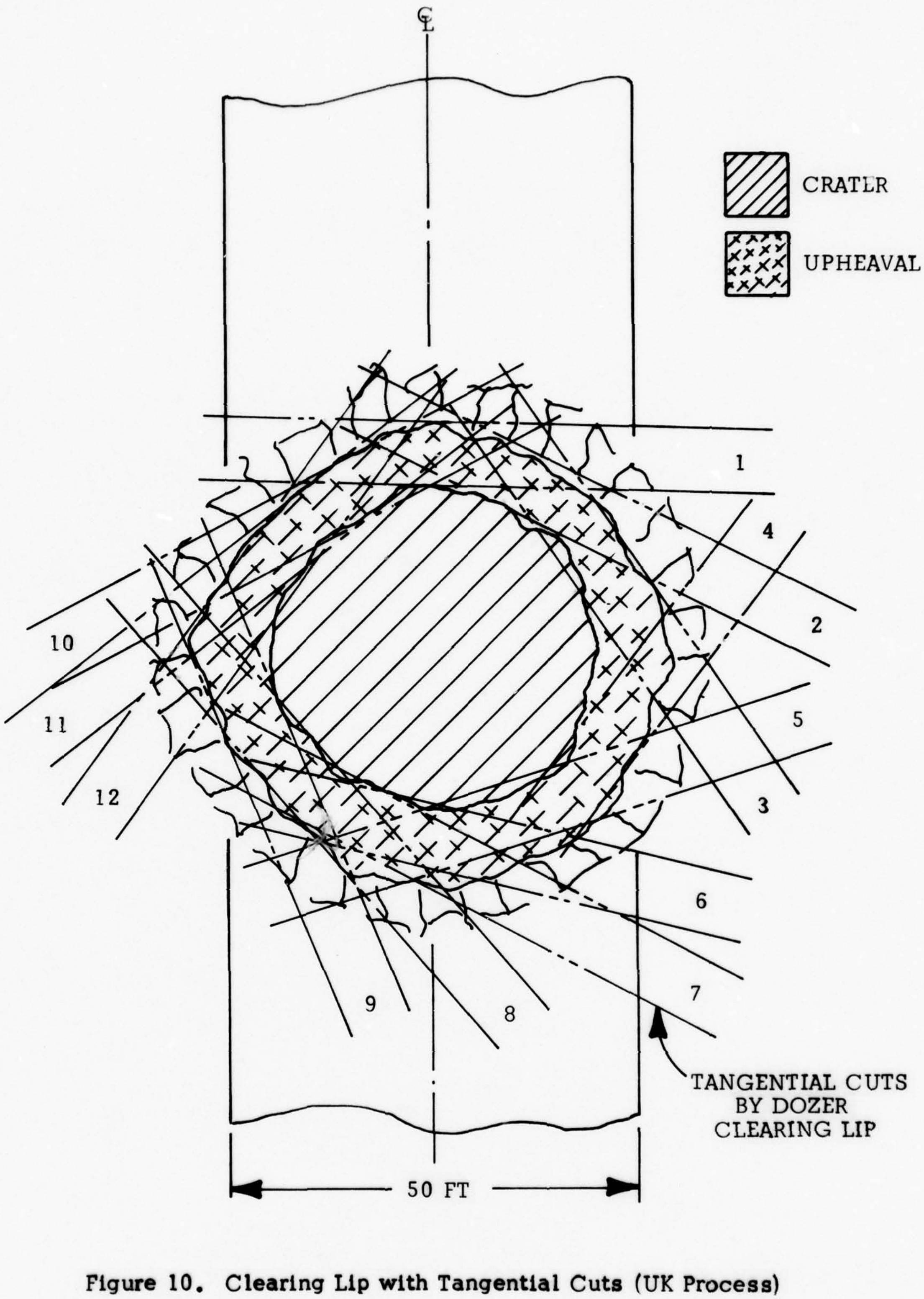


Figure 10. Clearing Lip with Tangential Cuts (UK Process)

The excavator can remove the crater lip during crater excavation and/or during removal of upheaved pavement. Specification for excavators in the 15- to 20-ton class show a capability for as many as six swings per minute. This is a machine design capability which is only achieved on a few trenching jobs. In actual use on a BDR task such as crater lip removal (see following paragraph) such speeds are unrealistic; since the operator has to hoe at the lip and pull the debris back, as well as to move the vehicle for different attacks, an average of 0.6 minute per swing is reasonable. The bucket width, which is narrower than a dozer blade, requires more swings. A bucket size of one cubic yard is commonly available in a 47-inch-wide pavement digging model. This model would require 34 swings to cut the lip, or 20.4 minutes for the task. There would still be material in the sectors away from the crater and the excavator could not dump all swings off the pavement. Thus, a dozer cleanup would still be required.

REMOVING UPHEAVED PAVEMENT

The task of removing upheaved pavement can be performed by several equipment items, in a sequence that lifts or prys up the heaved slab and then pushes or pulls it clear of the repair area.

The weight of a 12-inch thick runway slab that is 20-foot square is 56,000 pounds. In the Tyndall tests, 15-foot square slabs were encountered (about 31,500 pounds if 12 inches thick). To raise an entire slab clear of the repair surface would thus require a very large vehicle, with sufficient weight and balance to control such a lift. Many of the upheaved slabs encountered have been fractured into smaller pieces by the bomb blast, which reduces the average lift weight. This does not reduce the necessity to handle a full slab however.

Considering the maximum weights possibly required to be moved, a prying and sliding method is more feasible. Machines whose work patterns fit this requirement are:

1. Loader with 4-in-1 bucket or fork attachments
2. Dozer with blade
3. Dozer with ripper tooth
4. Excavator with scoop.

The actual breakout force of an upheaved slab approximates one-half of the slab weight, with adjustments for the angle of upheaval and any cohesion of the base course to the slab. For a 20-foot slab, consider a minimum breakout force of 28,000 pounds. This would require a loader to develop 28,000 pounds of lift in its fork linkages and hydraulics without tipping up on its front wheels. This requirement would eliminate most small loaders from consideration, although medium loaders could accomplish the task.

For a dozer with blade, 28,000 pounds of traction is required to push the slab up, plus the traction to move the vehicle weight. The tractive limit of the sand selected in this analysis is 12,700 pounds to the Bearcat and 21,900 pounds to the TD-20. (Refer to Appendix C, where T1 = N*G*C+W tan PHI). This first approximation indicates a heavier dozer is required for removing upheaval. The Caterpillar D8K has a tractive limit of 37,950 pounds

in this soil, adequate to perform the pushing out of the slab. Equipped with a ripping tooth, the D8 works on the dirt-covered pavement surface and develops less pull due to track slippage, approximately 33,000 pounds is available. Although this is still adequate, the required lifting motion is now restricted for the large slabs.

An excavator such as a Poclain 115-P can lift 11,000 pounds at a 25-foot radius over its end, and 7000 pounds over its side. To lift a full upheaved slab would require an excavator as large as the Drott 120 (34,000 pounds at 25 feet over its end), which is a tracked excavator. This would necessitate an equipment trailer to haul the vehicle to the repair site.

Loader with Forks

The loader with forks was used successfully in the Tyndall tests on upheaved pavement which was smaller than full slabs. Film sequences exhibited an ability to drive the forks under the upheaved pavement edge and lift/push the slab section onto firm pavement for subsequent spoiling. Some danger was noticed in the loader working near the crater rim, where a wheel could drop in and result in a stuck vehicle. The apparent cycle time for each upheaved slab section in the USAF films is approximately 1.5 minutes.

The loader with forks works better on small camouflet craters, where its ability to insert a single fork is an advantage compared to a dozer with blade.

Dozer with Blade

The dozer with blade is at a disadvantage in the camouflet mode, since it has difficulty getting a point into the small vent hole. An angle blade would be of advantage here.

In the open craters the dozer can operate more safely than the loaders and, when working from the crater interior (Figure 11), can develop both lifting and pushing forces from that angular approach. The time required for the dozer is approximately the same as for a loader. The dozer's lack of agility in approach and initial lifting is compensated by its better control in pushing the removed slab section away from the crater.

Dozer with Ripper Tooth

The dozer with ripper tooth is effective on smaller upheaved pavement slab sections. The dozer can insert the tooth with downward pressure into a crack and then develop a force vector upward and away from the crater. On large slab sections such as might be encountered in 750-pound bomb craters, the dozer with ripper has to also drag the upheaved slab section free by rotating it with pulls at the corner.

The dozer with ripper is very effective in a camouflet crater (Figure 12) since it can work directly into the vent hole and rip upheaved pavement loose. There is a possible danger of collapsing the undermined pavement, although the depth of the cylindrical vent hole (approximately four feet for small camouflet) should support the small portion of dozer weight over it. The vehicle's approach to the vent should be closely monitored by the crater NCO.

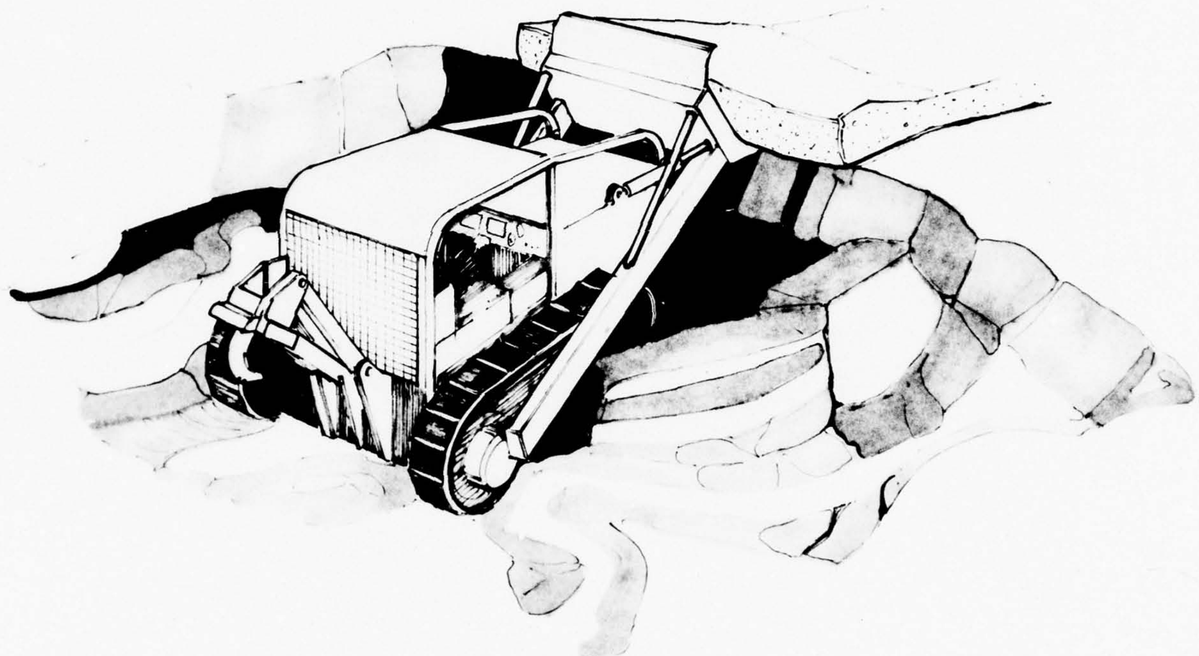


Figure 11. Dozer Working in Large Crater on Upheaved Concrete

Figure 12. Ripper Opening Camuoflet

Excavator with Scoop

The excavator with scoop is fairly efficient at removing upheaved pavement if the vehicle weight is sufficient to counteract the mass of large slab sections found at large craters (as large as 13-feet square in the Hokanson-Rollings report).

The excavator operator has full visibility of the work area. An excavator with an articulated arm rather than a telescoping boom can drag pieces away from the crater rim without collapsing the crater wall. Outriggers can be used to develop maximum lift and pull force; however, the cab-controlled hydraulic riggers (Figure 13) should be specified. This saves deployment time compared to manually deployed outriggers often used.

The 20-ton excavator can easily pull an upheaved slab 12 feet square loose in one minute on either open or camouflet craters. Generally, the loosened pavement must be spoiled by another vehicle.

EXCAVATING THE CRATER (UK PROCESS)

The select fill (UK) process for repairing craters requires excavating debris and plastically-deformed material from the crater prior to backfilling.

Dozers

Dozers have a difficult job excavating even a slope-sided crater. The fairly steep walls of the crater represent a poor dozing surface. Dirt must be cut down from the sides if steep and pushed up a slope to remove the material. The dozer can cut a lower-grade ramp out of the crater sides and use it; however, this then creates a larger backfill and subsequent compaction requirement. In small craters, especially camouflet, dozer use is not feasible.

Loaders

Loaders can work large crater excavation by working in the crater depositing bucket loads on the crater rim. However, this is also inefficient and requires a means of entrance to the crater by the loader.

Excavator

The best equipment item for excavating is the power shovel, hoe or, as described for upheaved pavement removal, the excavator. The excavator works from the crater rim, not the crater floor, and can easily average two swings per minute digging soil. A one-cubic-yard bucket clears the crater rapidly. Even in the camouflet mode, the excavator can easily dig out the vent cylinder and gain access to the true crater.

PLACING AND COMPACTING FILL

As the select fill is delivered at the crater area, two options are available to dump the fill:

1. Dump in temporary stockpile
2. Direct dump into crater.

Dump in Stockpile

The first method used when debris clearing tasks are still in process is to dump the fill in a temporary stockpile near the crater but out of the traffic patterns of other vehicles.

Figure 13. Excavator (Backhoe) Opening Small Crater

Dumping in a temporary stockpile requires an additional support operation comprised of the movement of the temporary stockpile into the crater. This operation can be performed by graders, loaders, and dozers.

Graders cannot perform well at this task, even with side-shift blades, since the blade is designed to deliver material perpendicular to the vehicle's travel direction. This forces the grader to operate tangentially to the crater rim, which precludes efficient or accurate placement.

The loaders equipped with four-in-one buckets and the dozers can push dirt directly from the stockpile to the crater and maneuver the payload over the rim where fill is needed. A dozer with a semi-U blade is well suited to drifting material in this manner since side spillage is reduced and a 12-foot-wide blade is a conventional size. From Caterpillar performance charts, a dozer with an S-blade (straight blade, modified U-shaped) can move 950 loose cubic yards per hour working up to 50 feet. Applying a bulking factor of 1.2 for loose stockpile operation, a maximum of 1140 cubic yards can be drifted per hour. Operator and job efficiencies will reduce this quantity in actual practice.

The loader, with its smaller bucket, can drift only approximately one-half as much material per hour as the dozer.

Direct Dumping

The second method is direct dumping into the crater. This method is obviously available only when the crater is ready for the addition of select fill, either on top of backfilled debris or into a completely excavated crater. Several investigators have noted a compacting action resulting from this crater fill method.

Direct dumping eliminates the dozer drift task, but requires closer coordination with other repair activities. The crater NCOIC must direct the truck as to when to and where to dump around the rim, and must also advise the driver during backing to the edge. A waiting time, not included in the computer analysis, occurs while the truck awaits direction. If only one truck dumps at one time, as in small craters, the queue time noted in the program (Q2 variable) deducts from team productivity.

COMPACTING THE FILL

Compaction is a construction process that has been and still is the subject of extensive theoretical and field research. Due largely to the non-homogeneity of soil, accurate predictions of compaction results are not available; the results of compaction depend on the material type, its size gradations, moisture content, and the amount of effort put into the task.

BDR must be accomplished even if no water is available for sprinkling the fill area. In addition, BDR must be attempted in rainstorms, if the strike has occured in such weather. Since reducing the amount of compaction time is an implicit goal of the BDR studies, the select fill material type and its size gradation are the principal analysis parameters that can be constrained. To establish a basis for tradeoffs, the problem then becomes:

> "What size of which material requires the fewest passes of a given compactor?"

The inverse question is:

"Which compactor requires the fewest passes in a given material?"

Any attempt to answer the first question is not appropriate for this BDR analysis since any particular selected material type and size may not be universally available, even though selecting a sample material would fit nicely in an equipment analysis since a single BDR compactor could then be advised. The selected alternative is to evaluate several compactors in several materials, which then implies different compactors for different air bases.

For this BDR study, an assessment of several compactors in different fill materials was made. The compactor types were:

1. 14,000-pound sheepsfoot roller
2. 14,000-pound rubber-tired roller
3. 12,500- pound vibratory drum roller
4. 1,000-pound vibratory plate.

Characteristics of the candidate compactors are listed in Appendix D.

The materials used in the analysis were:

1. Sand
2. Gravel
3. Crushed rock.

The sheepsfoot roller is a commonly used construction item. In use on earth/gravel fills it is rolled over the fill area until it "walks out"; that is, until the feet no longer penetrate the material. A sheepsfoot is most effective in lean clay material and produces acceptable results in sandy gravel fills.

The rubber-tired (pneumatic) roller can be used on most fill materials. Rollers of this type are available in weight classes up to 60 tons and use tire pressures of from 90- to 150-psi. Because of crater backfill characteristics that might include uneven debris nesting and because of the design or requirement to add select fill rapidly, the larger pneumatic rollers would require towing for the first compaction passes. The rolling resistance in 12-inch loose fill thicknesses (lifts) will approach 200 pounds per ton of vehicle weight. A 60-ton pneumatic roller would therefore require 12,000 pounds of tractive effort first to propell itself (or to be towed). In the U.S. Army Waterways Experimental Station (WES) tests of 1963 (Reference A-19), a 50-ton roller produced maximum density in crushed limestone at 32 passes. This compacted surface then sustained 500 traffic passes of a 50,000 pound load cart.

In a 1968 test sponsored by the U.S. Air Force (Reference A-19), WES compared three vibratory drum rollers to a 50-ton rubber-tired roller in sand, limestone and lean clay. The pneumatic roller performed best in sand and lean clay, requiring only 25 percent as many passes in lean clay as a heavy, low frequency, vibratory roller, for equal compaction. This vibratory roller was most effective in crushed limestone; a medium weight, low frequency vibrator was effective in sand.

Maximum travel speeds are not significant on a work area as small as a crater; however, for information effective speeds are:

1. Sheepsfoot roller: 264 feet/minute
2. Rubber-tired roller: 440 feet/minute
3. Vibratory drum roller: 528 feet/minute
4. Vibratory plate: 80 feet/minute

On the basis of the literature surveyed and discussions with construction engineers on runway, road and earthfill dam prijects, the following advantages and disadvantages of each roller are listed below:

1. <u>Sheepsfoot</u>
   a. Advantages
      (1) Easily monitored effectiveness because roller walks out when material is compacted;
      (2) Compaction pressure can be varied by ballasting main drum (150 psi to 750 psi).
   b. Disadvantages
      (1) Most effective in lift depths equal to or less than length of feet (normally 7 to 9 inches long);
      (2) Usually requires five to seven passes to achieve best density;
      (3) Not effective in crushed rock or concrete debris.
2. <u>Rubber-Tired</u>
   a. Advantages
      (1) Effective in lifts up to 2 feet deep, including crushed stone;
      (2) Achieves good results in two to four passes;
      (3) Can transport without road damage.
   b. Disadvantages
      (1) Must be monitored to avoid overworking the fill, with subsequent loss of strength;
      (2) Optimum moisture content must be maintained to achieve consistent results.
3. <u>Vibratory Drum</u>
   a. Advantages
      (1) Effective in lifts up to 18 inches;
      (2) Achieves good results in sand-gravel fills and finely crushed stone.
   b. Disadvantages
      (1) Vibration frequency should be adjusted for best results in different materials;
      (2) Drum is not effective in debris and can be damaged by sharp corners.
4. <u>Vibratory Plate</u>
   a. Advantage
      (1) Small, easily maneuvered in small craters, easily transported.
   b. Disadvantages
      (1) Small area covered; slow rate recommended
      (2) Requires a crane or similar lift to deploy.

In addition to these compaction equipment items, the compaction capability of the other BDR vehicles, such as crawlers and dozers, must be assessed. Crawler tractors have good traction in the fill area, but have a low ground pressure. This low crawler ground pressure (approximately 8.4 psi for an International Harvester TD-20, for example) which allows crawlers to achieve high mobility in soft ground, makes them an inefficient compactor. The principal benefit of crawlers in the crater task is the crushing and settling of debris which results from the crawler weight traversing the initial backfill.

At a symposium on compaction of soils, presented at the 67th Annual Meeting of the ASTM, W.E. Winnitoy presented a paper on "Ultimate Densities and Strength Considerations of Base and Subgrade Soils" in which he related vertical stresses in soil to loads by the Boussinesq equation:

$$S = p\left[1 - \frac{Z^3}{(a^2 + Z^2)^{3/2}}\right] \qquad (1)$$

where:

S = vertical stress below center of a loaded circular area

p = unit load, psi

Z = depth below center of loaded area

a = radius of loaded area.

From this relationship, a standard truck dual wheel loaded at 9000 pounds produces 80 psi loading. This achieves a vertical stress of only 40 psi at a depth of 8 inches. To visualize the compaction effectiveness of this stress, the stress is compared to cemented rock with a bearing strength of approximately 110 psi; well-compacted sand bearing strength of 100psi, and loose, dry sand bearing strength of 25 psi.

A rubber-tired dozer such as the Clark 280 develops a ground pressure of approximately 27 psi, not an effective compaction pressure. In addition, dozers of this type will have trouble negotiating the initial backfill of debris.

From the data available, it appears that for the range of conditions for BDR, the pneumatic roller and the vibratory drum are the best suited.

A typical pneumatic roller of 14,000 pounds (unballasted) has eight rear tires sized 14.00 x 24. It has a 75 - 100 horsepower engine and can turn in an 18-foot circle. This size tire has a ground contact area approximately 18.4 square inches at an inflation pressure to 60 psi; if 70 percent of the vehicle weight is on the rear tires, the ground pressure is 65 psi, which is less than the loaded truck discussed earlier. This analysis emphasizes the need for ballasting. If the same vehicle is ballasted to 40,000 pounds with sand or water, the tire load increases to 3500 pounds. Increasing the tire pressure to 90 psi produces a ground pressure to 100 psi, which is a more effective compaction pressure.

A vibratory drum roller of 14,000 pounds typically has 7800 pounds on a 60-inch-long drum. This is 130 pounds per lineal inch; manufacturers quote applied force per drum at approximately 22,000 pounds when vibrating 1100

to 1600 vibrations per minute. The force per square inch obviously varies; as the drum compacts the loose fill, less drum surface is in contact with the soil. At full compaction, the drum area is approximately 120 square inches, which would equate to a ground pressure of approximately 180 psi. Turning diameter is approximately 18 feet (Figure 14) which is acceptable in large craters.

A vibratory plate compactor about 2 feet square is normally vibrated 2000 to 3000 times per minute. A 1000-pound unit can produce about 10,000 pounds of force, or 16 psi. This is a very small compaction pressure and is adequate for a lift depth of only about 4 inches. It was considered in this study as a possible means of compacting small craters, but since it requires lifting the vibrator in and out of the crater, it is not effective.

The problem to be resolved in BDR is to determine how many passes of an appropriate compactor is required to provide a CBR adequate to support repetitive crossings by strike aircraft. Based upon load cart tests from Hokanson and Rollings work, it appears that a minimum CBR of 25 is required for base courses and a CBR of 9 for sub-bases for single wheel loads of 30,000 pounds.

The California Bearing Ratio is proportional to the number of passes of a given compactor, the weight of the compactor (or effective weight in the case of vibratory compactor, the speed of crossing the fill area, the specific soil being worked and the optimum moisture content of the soil for maximum density.

Optimum moisture content is difficult to maintain in deep fills, partially due to water migration during compaction and partially due to the difficulty in establishing optimum. Fortunately, the soils generally used for select fill,e.g. sand, sandy gravel, compact better wet of optimum than is possible on the dry of optimum side. This allows the BDR teams to operate on the wet side of optimum, which is an obvious advantage for repairs during rainfall. For example, Figure 15 is a composite plot of data from Reference A-19 of coverage versus density for a vibrating roller on sand and limestone as a function of moisture content.

The Waterways Experiment Station produced high compaction levels in over-wet crushed aggregate base courses with 32 coverages (passes) of a 90 psi rubber-tired roller, (Reference A-19). A CBR of about 96 was achieved at this compaction effort. Eight coverages produced a CBR of 56. Four-inch lifts (layers) were used in those tests. Tire pressures of 150 psi on a 60-ton roller produced a CBR close to 66 in 16 passes. This density did not deteriorate appreciably under heavy load testing.

A comparison of accomplished compaction and required density leads to a recommended compaction effort of 4 passes on the sub-base (below the one-foot fill depth) and 4 passes on the top foot with a grader cut prior to the last two passes. The subgrade effort can be accomplished by towing the compactor with a dozer to provide sufficient mobility in the loose fill.

An acceptable CBR can be tested for by numerous devices; cone penetrometer, shear plates and grouser plates. These devices are described by E.T. Selig (Reference A-24).

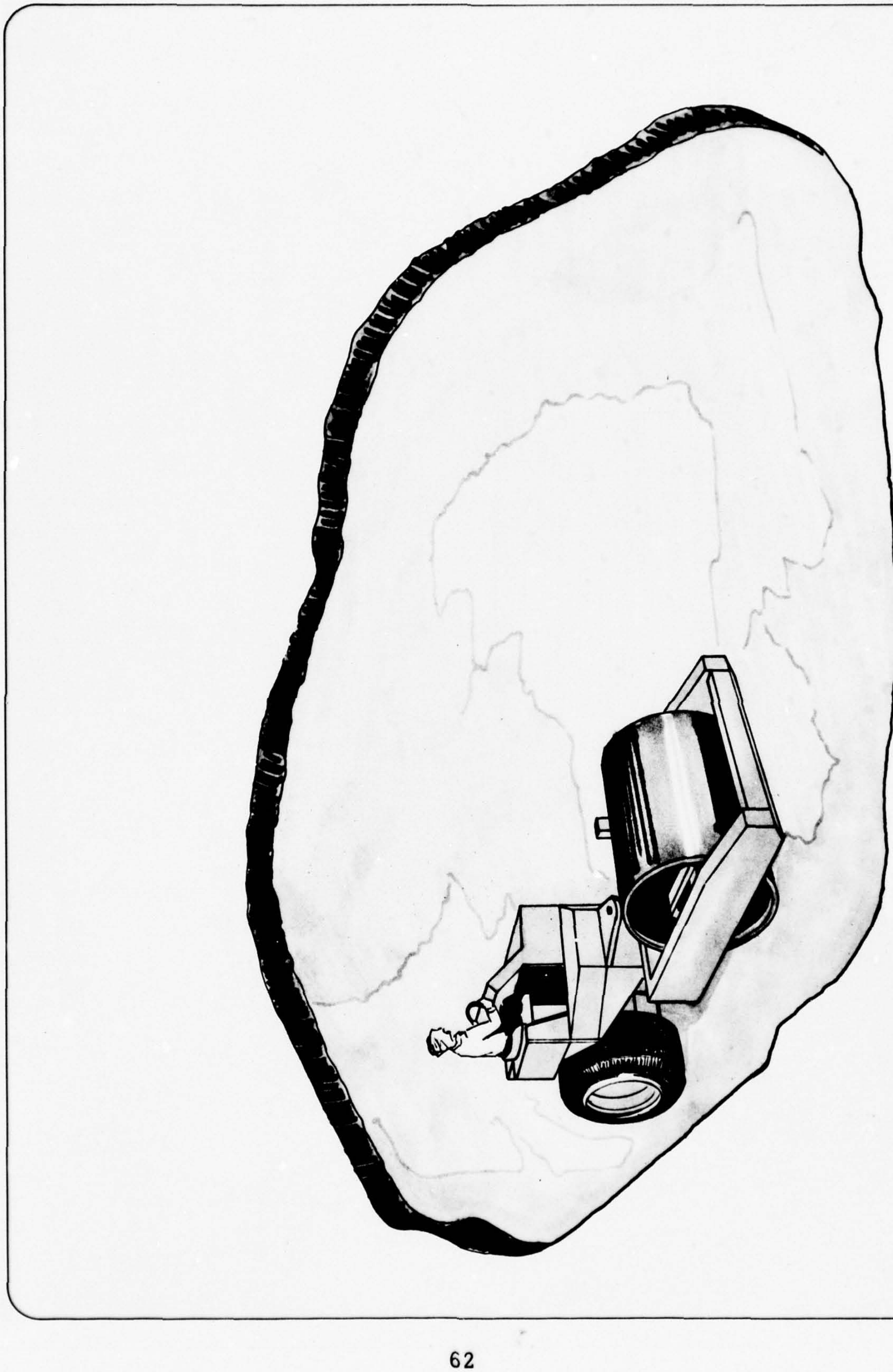


Figure 14. Vibration Drum Roller Turning in Large Crater

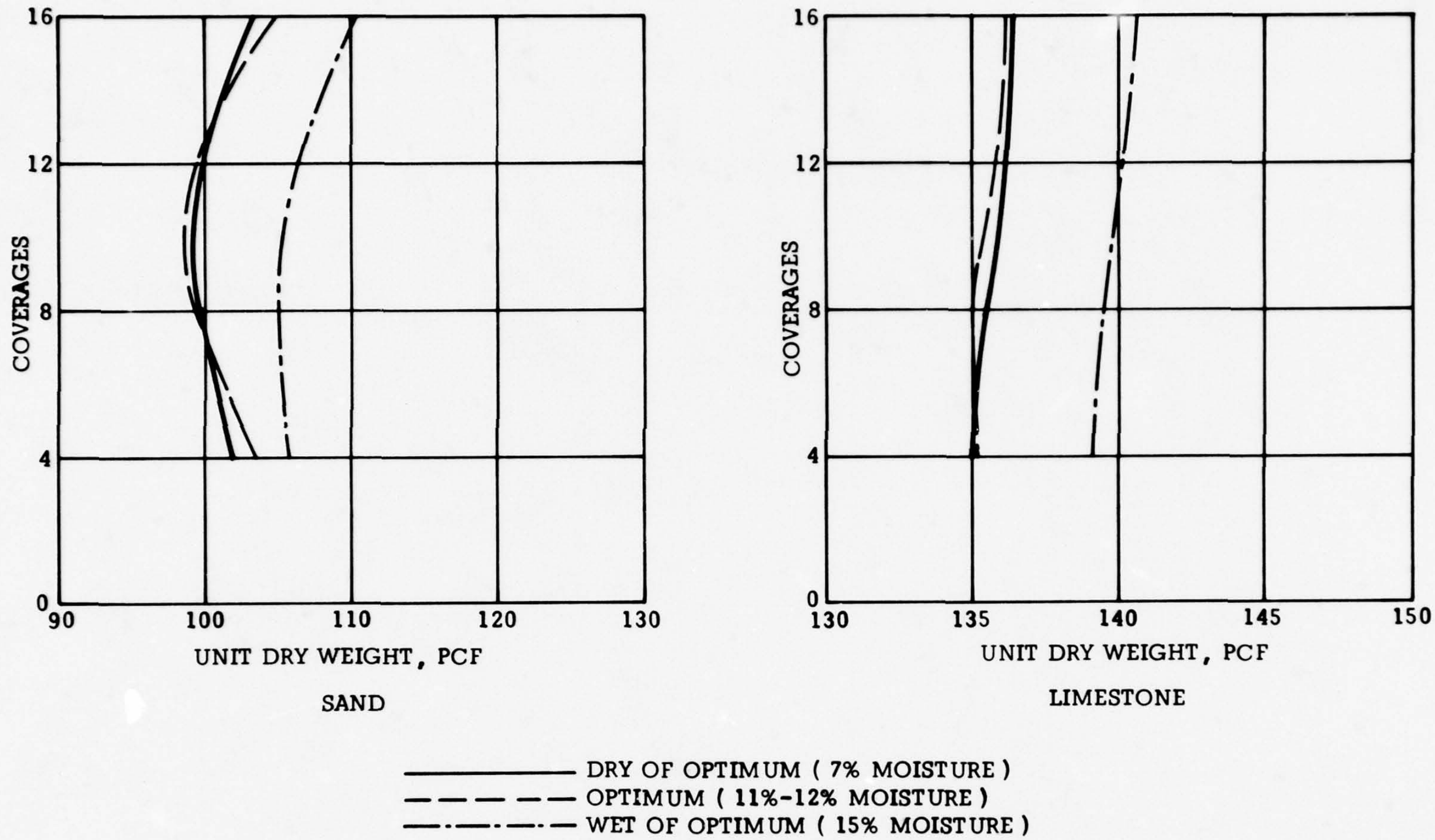


Figure 15. Coverages versus Density - Vibrating Rollers on Sand and Limestone

FINISHING

The final tasks on the crater repair are grading and sweeping. The present graders are adequate for the task; the area is small and will be compacted. The most effective way to increase grader effectiveness on BDR is to minimize the number of passes.

In the observation of BDR films, it was observed that fixed-frame graders were used by the repair teams. An articulated grader such as the Caterpillar 12G has a wheelbase of 21.9 feet and a turning circle of 24 feet. This compares to a grader such as Galion's T-500 with a wheelbase of 19.2 and a turning circle of 36 feet. In confined areas, where maneuverability is desired, an articulated grader has a distinct advantage. On straightaway distances, such as runway clearing between large craters, articulation is not required.

The parameter of wheelbase is of interest in obtaining level grades. Since a grader blade is carried between its axles, the distance aft from the front axle directly affects the finish quality. Consider an example where a blade is mounted directly behind the front axle. As the front wheels rise and fall over surface obstacles, the blade exhibits the same height change. As the location of the blade is moved rearward, the blade height change is linearly reduced as the cotangent function of the wheelbase (a fixed height obstacle is assumed here). This relationship is seen at its extreme utilization in the land-leveling machines used in irrigation farming.

With the above factors in mind, the principal characteristics of graders considered were wheelbase, horsepower, blade width, and turning circle. Candidate vehicles are listed in Appendix D. As in loaders and trucks, other base activities may influence the grader selection.

Time savings due to articulation are difficult to assess analytically. An operator's skill with a tilt-wheel steered grader may exceed that of one with an articulated or all-wheel steered grader. Actual field comparisons in close working quarters are needed to quantify the difference.

The tradeoff to be made in the BDR sequences involves the times required to:

1. Fill and compact, then grade, refill and compact and final grade, versus
2. Overfill and compact, then finish grade.

This tradeoff is examined in the next section.

Sweepers considered were the towed rotary drum brooms, self-propelled brooms and vacuum sweepers. Little comparison data is available on sweepers, however some quality considerations are discussed in Section VIII. Again, field observations are required to quantify the sweeping tradeoffs.

SECTION VIII
BDR SEQUENCE ANALYSIS

This section assembles the data developed in previous sections into a complete BDR process and time/quality analysis for the three BDR processes:

1. AFR 93-2 process
2. United Kingdom (UK) process
3. Advanced fill process.

Each process is discussed as regards various sequencing and equipment mix options for reducing the task times and hence the total repair time. Equipment utilization is examined to maximize the total time each equipment item is directly supporting BDR.

Each process is analyzed with three equipment mixes:

MIX A. Present AFR 93-2 equipment types and quantities with optimized equipment sequencing .

MIX B. Substituted commercial equipment in the AFR 93-2 quantities.

MIX C. Substituted commercial equipment in recommended quantities.

A scenario is established for large and small crater repair problems and the repair areas are detailed. The times in each BDR task are developed and process task tables are provided.

The equipment mixes each are comprised of some combination of available off-the-shelf equipment listed in Appendix D and analyzed on a task-by-task basis in Section VII. In Mix B and Mix C, several minor modifications were recommended. As discussed in Sections VII and IX, these minor modifications (sight holes in buckets, larger loader buckets, ballasting) will increase safety and the probability of regularly achieving planned operational efficiencies in a range of environmental conditions. However, the minor modifications do not generally decrease task times. Instead, the modifications should be considered as an insurance against variations in operator skill levels, climate, and other related conditions.

Major modifications and new-concept equipment were also considered in selecting the equipment mixes--these are also discussed in Section IX. For the above-noted reasons and others noted in Section IX in detail, these were not included in the equipment mixes.

LARGE CRATER REPAIRS - AFR 93-2 PROCESS

Given the airfield layout of figure 16 , the expedient runway "worst case" repair problem is to be configured as shown. The three 750-pound bomb craters for the problem are spaced as shown on Figure 17 .

A 750-pound bomb creates a typical crater such as that shown in Sections III and V. Dimensions are as in Table 4. The debris dispersion was analyzed in Section V and depicted in Figure 4 . The repair area layout is shown in Figure 18 .

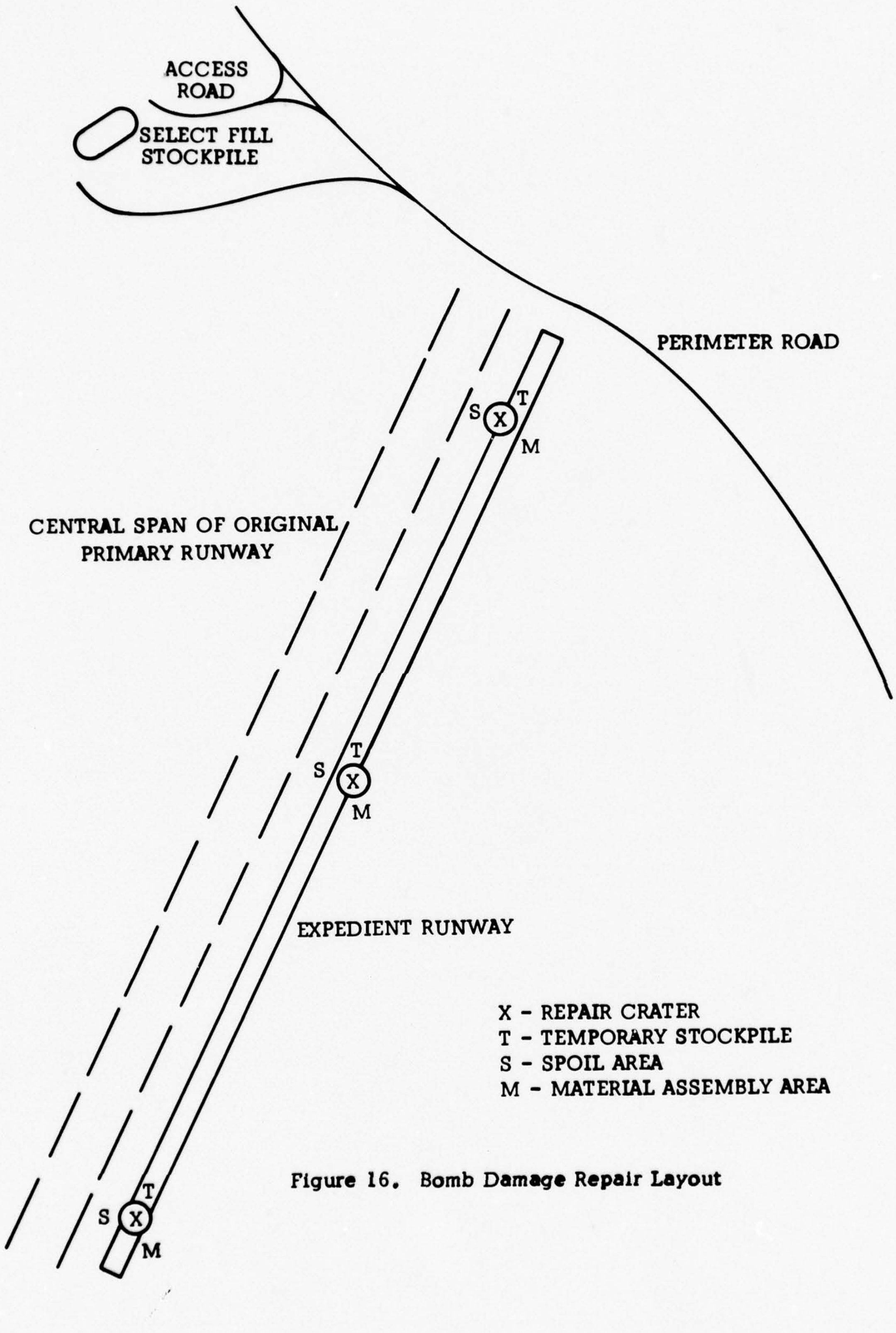


Figure 16. Bomb Damage Repair Layout

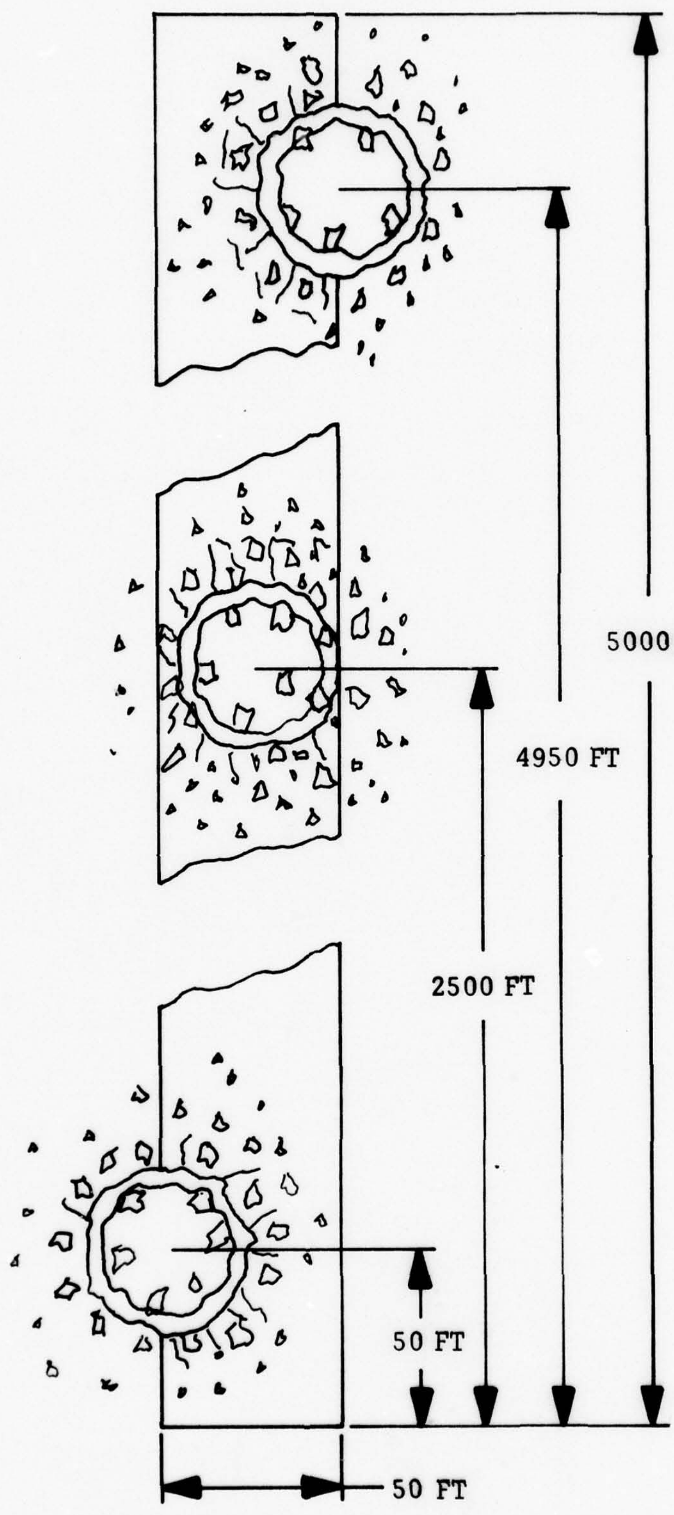


Figure 17 . Bomb-Damaged Runway - (3) 750 Pound Craters

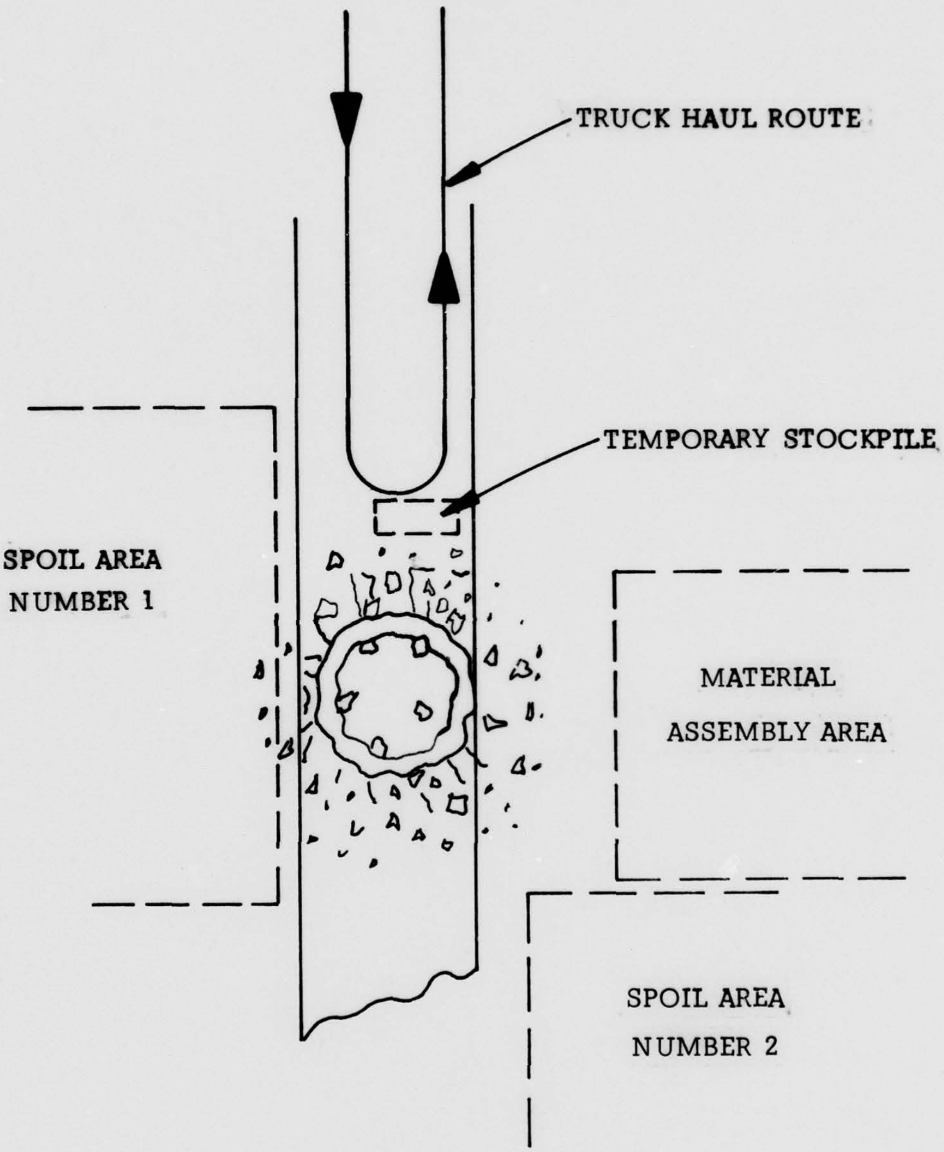


Figure 18. Large Crater Repair Area

The AFR 93-2 process will be described, using the three mixes of equipment. Some improvement can be achieved in the AFR 93-2 process by optimizing the use and sequencing of vehicles. These changes in the process are discussed as they occur in the following paragraphs.

Initial Team Deployment - Mix A

The baseline analysis of the AFR 93-2 process is conducted (a) with Equipment Mix A, with the existing detailed within-task sequencing, and (b) with an alternate within-task sequencing. For reference, the AFR 93-2 BDR equipment list is shown on Table 22.

TABLE 22. AFR 93-2 BDR EQUIPMENT (MIX A)

Article	Nomenclature	Quantity
28	Truck, dump, 5 ton 4x4	15
30	Tractor, full track Sz4	3
31	Grader, 6x4	3
32	Tractor, IW55	5
33	Loader, scoop-tired, 2.5 CY	7
34	Roller, towed, vibrator	3
35	Sweeper, towed, rotary	2
36	Sweeper, vacuum, self-propelled	2

From the BDR crew assembly area, the crew deploys to two locations. One loader and the fifteen haul trucks go directly to the select fill stockpile. The rest of the crew goes to the damage area. Coordination is achieved with two-way radios.

During the travel to the damage areas, the graders and rubber-tired dozers are directed to clear rubble to create clean haul roads for the trucks hauling select fill. Except for these deployment patterns, the crater repair is discussed on a per-crater basis.

Debris Spoiling or Backfill

At the first crater, a decision is made to spoil or backfill debris. The basis for this decision is the time required for spoil, backfill or a combination unless a specific BDR sequence is directed.

The analysis of this tradeoff is made from the computer runs comparing the time lines of rubber-tired dozers, tracked dozers, and rubber-tired loaders at these tasks. The population to be spoiled or backfilled varies, depending on the selected working distance.

Figure 19 compares these tasks at various distances from the crater. Rubber-tired dozers and loaders have a definite time advantage over crawlers in both spoiling and backfill tasks. Therefore, the two loaders are used to spoil debris until one loader is required to unload matting. The other loader continues spoiling debris. The crawler dozer meanwhile is backfilling alone.

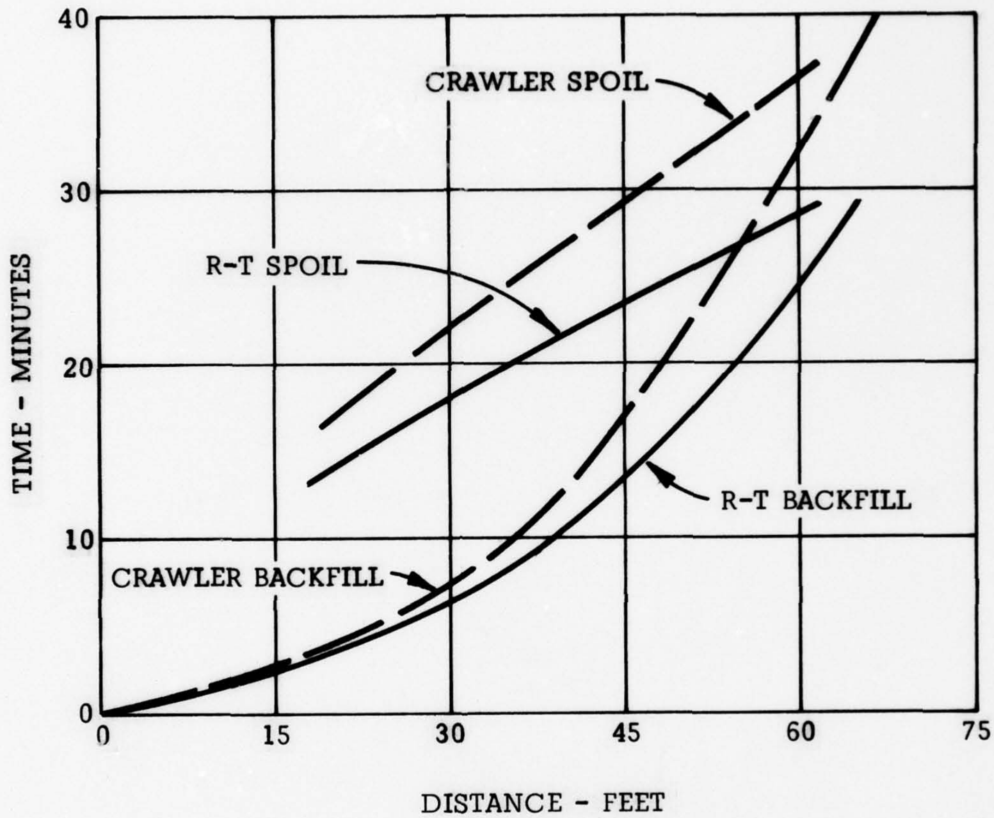


Figure 19. Large Crater Spoil and Backfill Times at Varying Distances

The least time to backfill all debris is 37 minutes. The least time to spoil all debris is 34 minutes. A crater of the 750-pound type has a volume of about 220 cubic yards. All except the final 12 inches can be backfilled by debris in the AFR 93-2 process.

The entire pavement repair area, 3374 square feet, will thus require 3374 cubic feet of compacted select fill. The crater below the concrete surface is about 5400 cubic feet.

Since the runway area is the only area of concern, debris which is off the runway can be ignored except in the mat assembly area. From Figure 20 the prime area of interest is the 54-foot-wide by 160-foot-long area (8640 square feet) out of the circular damage area of:

$$\text{Area} = \frac{\pi \cdot 160^2}{4} \qquad (20{,}106 \text{ sq ft})$$

Assuming a uniform debris distribution in the circular area, then only 43 percent of the debris 5 feet square and larger is on the runway and is used for backfill.

In addition, a mat assembly area has to be cleared. The 4400 square feet for this area can be cleared by the grader, since it contains smaller debris.

The task times developed in Section VII can now be adjusted accordingly. For backfill, 43 percent of the time and volume results in a crawler work time as follows:

$$(0.43)(38.3) \text{ min.} = 16.5 \text{ minutes}$$

The volume of backfill represented by this effort is 43 percent of the concrete volume, and approximately 50 percent of the soil debris:

$$(0.43)(3374) \text{ cu. ft.} + (0.5)(7162) \text{ cu. ft.} = 5030 \text{ cu. ft.}$$

Using the crawler to backfill assigns the spoiling task to the loader.

One loader spoiling all debris over 40 feet from the crater required 25 minutes. Using the approach that only the runway requires spoiling, the time is 65 percent of this, or 16.3 minutes for one loader and about 9 minutes for two loaders.

The foregoing analysis thus defines several task times for the critical path diagrams of the repair processes.

One piece of data not explicit in these calculations is that the time required to spoil upheaved pavement after removal is included in the spoil times. This was a consequence of not differentiating between upheaved pavement area and crater area in the distribution theory. The removal times are computed later in the section, but the spoil times are accounted for in this task, even though the spoil cannot be completed before removal finishes.

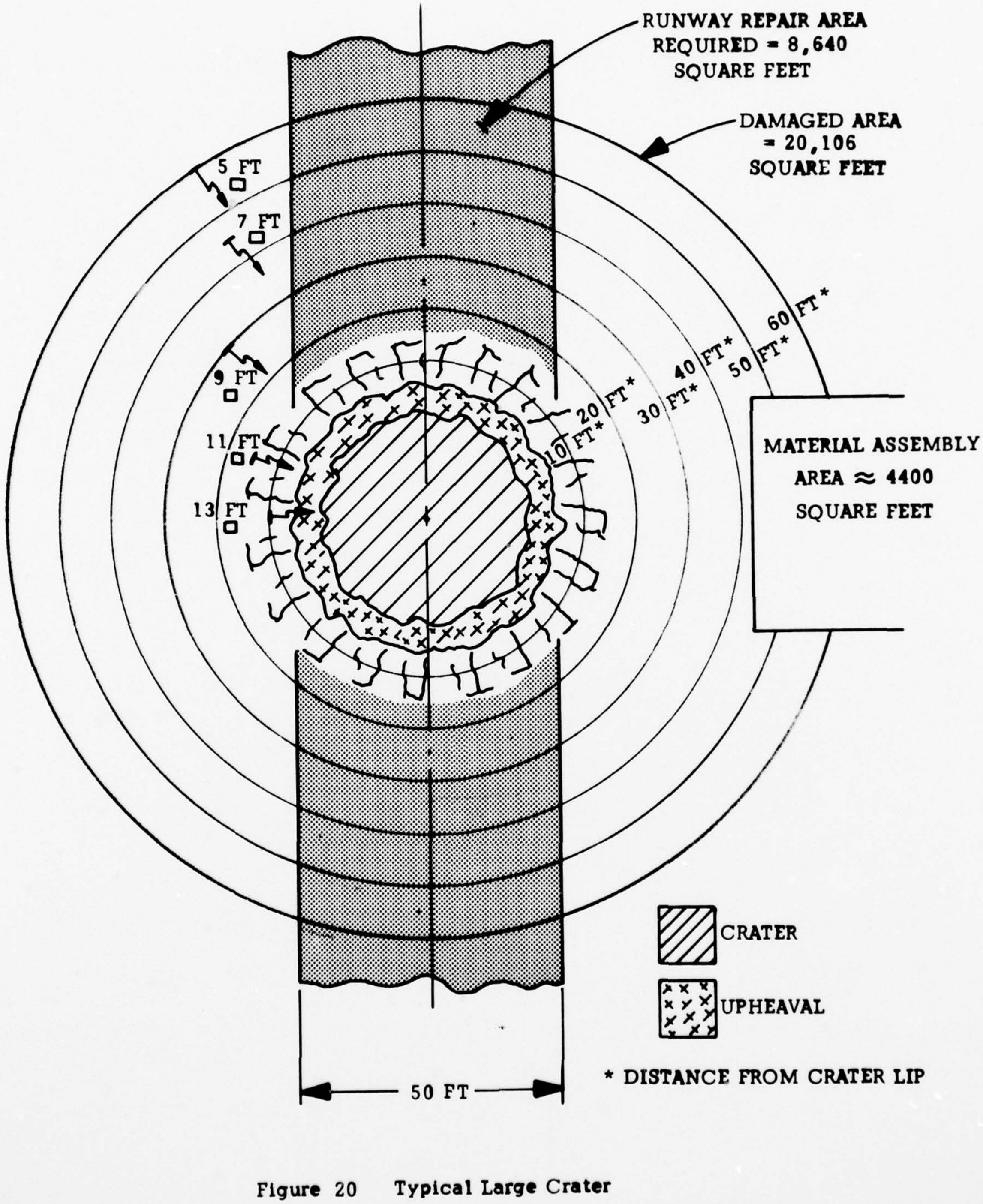


Figure 20 Typical Large Crater

Select Fill Haul and Placement

Backfilling 43 percent of the concrete debris only provides 1450 cubic feet of concrete fill and 3580 cubic feet of soil ejecta. Applying the bulking factor of 1.6 for concrete increases that fill quantity to 2320 cubic feet in the crater. Compacting the loose ejecta by a factor of 0.77 reduces the soil ejecta to 2750 cubic feet. Therefore, an additional 870 cubic feet is required to fill the crater to the top of the base course. At the bulking factor of 1.15 for a sandy fill material, the required haul volume will be 4750 cubic feet to provide a 12-inch layer of fill. Each haul truck has a wait time of five minutes at the base stockpile, since there is only one loader for fifteen trucks. Thus, the five trucks assigned to each crater require 140 minutes to haul eleven loads each at 3.2 cubic yards per load. This task is accomplished by dumping in a temporary stockpile area for the first six trucks (20 minutes). After this, the trucks dump directly into the crater while the dozer moves the temporary stockpile into the crater. This part of the fill task takes the crawler only a few minutes, since it has a shuttle dozing productivity of 1200 cubic feet per hour (in terms of the loose stockpile material). The loader specified in AFR 93-2 with a 2-1/2 cubic yard bucket would require 8 minutes for this task since its blade width is 8 feet compared to the 12-foot blade of the crawler.

The trucks complete the hauling task in 2 hours 12 minutes; with each truck waiting 55 minutes of this time because the single loader requires 12 minutes to load 15 trucks once each.

Pavement Upheaval

When the backfill task is completed, the crawler should be utilized in removing upheaved pavement. On a large crater, approximately 20 pieces of pavement averaging 10 feet square are to be removed. At a machine cycle time of 1.5 minutes per piece, the upheaval task requires 30 minutes.

The one loader available per crater now spoils the removed upheaval, finishing in 30 minutes.

Alternate AFR 93-2 Task Sequencing - Mix A

An alternative approach would have the crawler continue backfilling while a loader with forks removes upheaval. Since one loader does not start unloading matting until 1:05, it can remove upheaval until the dozer finishes at 0:47.

The hauling task completes in 135 minutes. Since the loader completes the spoiling task just after the crawler completes removing upheaval, the loader could be reassigned to the base stockpile. The completion time for placing all fill by this variation is 101 minutes after starting work at the crater. Thirty minutes are expended in assembling and deploying the crew and selecting the craters to be repaired.

This thirty minutes will have to be reduced to attain a 60-minute repair time or even to approach a two-hour BDR.

By the analysis of the AFR 93-2 method, at the end of hauling fill a total time of 160 minutes has elapsed. For the modified AFR 93-2 method analyzed, 131 minutes are required.

Compacting

Tasks remaining are compacting, grading and sweeping for both time lines.

The vibrator roller in the AFR 93-2 equipment list is towed by an IW 55 tractor. The tractor develops approximately 75 horsepower and has approximately 6500 pounds of traction available at 3 mph. Since the roller and tractor together have approximately 2200 pounds of rolling resistance in the soft fill, there should be little problem in traversing the crater fill area. The combination has a turning circle of about 34 feet, which will require straight compaction patterns rather than circular. The 5-foot-wide roller requires approximately twelve passes to cover the area once, with only minimum overlap. At 5 mph and 1.0 minute fixed time per pass, this only provides one coverage per 15 minutes. Since the minimum compaction effort was assessed at four coverages on both the sub-base and the select fill, the total time will run 120 minutes.

Grading

The grading effort should be done in two phases: one leveling coverage after the first compaction pass and a second finishing cut when compacting is finished. The grader requires two minutes per pass; the repair area of approximately 3400 square feet requires six passes to cover the area in one direction. Following the last compaction run, the grader makes a thin finishing cut in another 12 minutes. The greatest time is spent stopping, reversing and stopping again on each pass. This still is less time than driving a loop pattern, since the graders require a minimum turning diameter of more than 24 feet, which must be even larger to align the grader for the next pass with minimum overlap and no misses.

Final Sweeping

Final sweeping is accomplished by the towed broom in a spiral pattern which begins at the crater center. This continuous pattern works the dirt and fine debris into a windrow which is swept outward by successive passes until it is off the runway. An effective sweeping width of 6 feet requires four and one-half laps across the 54-foot by 160-foot area. At a speed of 3 mph, this final sweeping requires 24 minutes.

The vacuum sweeper, under dry conditions, will perform in about the same time; however, its work pattern can vary and may begin before final grading completes.

Summary of AFR 93-2 Process, Equipment Mix A Analysis

The task times for the AFR 93-2 process with Mix A is shown in Table 23.

Modified AFR 93-2 Equipment List - Mix B

At this point in the analysis, equipment items were substituted into the AFR 93-2 inventory on a one-for-one basis. The substitutions were assessed to be more productive as a result of the equipment evaluations documented in Section VII.

TABLE 23. AFR 93-2 PROCESS TIMES

LARGE CRATER EQUIPMENT MIX A

TASK or (subtask)	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. Crawler	0:30	0:47	17 min.
Move Temp. Stockpile	1. Loader A	0:40	0:48	8 min.
Spoil Debris	1. Loader A	0:30	0:39	9 min.
	2. Loader B	0:30	0:39	9 min.
Spoil Upheaval	1. Loader A	0:48	1:18	30 min.
Remove Lip	1. Crawler	0:30	0:47	(Included in backfill)
Remove Upheaval	1. Crawler or	0:47	1:17	30 min.
	2. Loader w/Forks B	0:40	1:05	30 min.
Excavate	1. N/A	N/A	N/A	N/A
Load	1. 1/3 Loader (#7)	0:25	2:37	132 min.
Haul	1. (5) 5-Ton Trucks	0:25	2:40	135 min.
Grade: Cleanup	1. 3 Graders, Runway Road	0:20	0:45	25 min.
	2. 1 Grader, Mat Area	0:45	1:03	18 min.
	3. 1 Grader, Repair Area	1:03	1:30	27 min.
Grade: Level	1. Grader, 1st Cut	3:10	3:22	12 min.
	2. Grader, Finish	3:40	3:52	12 min.
Compact	1. Vibrator on sub-base	0:48	1:48	60 min.
	2. Vibrator on top course	2:40	3:40	60 min.
Sweep	1. 2/3 Rotary	1:30	4:00	150 min.
	2. 2/3 Vacuum	1:30	4:00	150 min.

The changes made were:

(15) 10-ton trucks for (15) 5-ton trucks

(1) 3-1/2-CY loader for (1) 2-1/2-CY loader

(1) Self-propelled vibratory roller for (1) towed vibratory roller.

The larger trucks, supported by a larger loader, complete the hauling task (Table 24) in 60 minutes. Trucks wait four minutes per cycle, or 20 minutes each during the task of hauling five loads each.

During the backfill and spoiling tasks, the trucks dump 42 cubic yards of fill in a temporary stockpile. This will take a dozer 56 minutes to doze into the crater. Since the one loader goes to unload matting at 1:05, the other loader completes the removal and spoiling of upheaval alone and finishes at 1:12. This loader now assists the dozer at drifting the stockpile into the crater and the two vehicles complete at 1:32.

The self-propelled compactor, with a turning radius of 20.4 feet, can operate in a circular pattern as the crater is nearly filled. This allows the compactor to finish the sub-base while the select fill is being drifted into the crater. Since the turning time is eliminated, the 8-foot-wide compactor can cover the crater area four times in 15 minutes.

The better coordination of equipment is allowed by the reduced hauling time for select fill. The net gain by this mix is one hour and 35 minutes. The time line for this equipment mix is shown in Table **24**.

AFR 93-2 Process - Mix C

If two self propelled compactors per crater were used, the compaction time would approach 15 minutes, and the total time would be 130 minutes. The significant element has now become the dozing of the temporary stockpile: **45 minutes. Adding a rubber-tired dozer rearranges the times as shown in Table 25, for a total time of one hour 56 minutes.**

Adding any more vehicles will make the repair area too congested for efficient vehicle utilization, since this makes a total of four vehicles active in the crater area during the early stages.

LARGE CRATER REPAIR - UK PROCESS

The United Kingdom (UK) process, or Rapid Runway Repair, is based upon total excavation of the crater and filling the excavated crater with select fill. A pre-assembled trackway is then unrolled manually over the compacted fill. For the scope of this study, only the preparation of the crater before capping with the trackway is compared to the AFR 93-2 process.

The analysis uses the same crater, debris and equipment parameters as in the 93-2 analysis. The UK equipment in the film included an excavator (tracked). This item will subsequently be factored into the time line in Equipment Mix C.

In this process all debris is spoiled, the crater is excavated of debris, fallback and plastically deformed material, and select fill is placed and compacted.

TABLE 24. AFR 93-2 PROCESS TIMES

LARGE CRATER - EQUIPMENT MIX B

TASK	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. Crawler	0:30	0:47	17 min.
Spoil Upheaval	1. Loader A	0:40	1:15	35 min.
Spoil	1. Loader A	0:30	0:39	9 min.
	2. Loader B	0:30	0:39	9 min.
Remove Lip	1. Crawler	0:30	0:47	(Included in backfill)
Remove Upheaval	1. Loader w/forks B	0:40	0:58	30 min.
	2. Loader A	1:00	1:12	"
Drift Stockpile	1. Crawler	0:47	1:32	45 min.
	2. Loader A	1:15	1:32	"
Load	1. (1/3) Loader #7 3 1/2 cy.	0:25	1:21	56 min.
Haul	1. (5) 10-Ton Trucks	0:25	1:25	60 min.
Grade: Cleanup	1. 3 Graders, Runway Road	0:20	0:45	25 min.
	2. 1 Grader, Mat Area	0:45	1:03	18 min.
	3. 1 Grader, Repair Area	1:03	1:30	27 min.
Grade: Level	1. Grader, 1st cut	1:50	2:02	12 min.
	2. Grader, Finish	2:05	2:17	12 min.
Compact	1. Vibrator, S/P on Sub-Base	1:00	1:15	15 min.
	2. Vibrator on top course	1:35	2:05	30 min.
Sweep	1. 2/3 Rotary Broom	1:15	2:25	70 min.
	2. 2/3 Vacuum	1:15	2:25	70 min.

TABLE 25. AFR 93-2 PROCESS TIMES

LARGE CRATER EQUIPMENT MIX C

TASK or (subtask)	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. R-T Dozer	0:30	0:47	17 min.
Spoil Upheaval	1. Loader A	0:40	1:15	35 min.
Spoil	1. Loader A	0:30	0:39	9 min.
	2. Loader B	0:30	0:39	"
Remove Lip	1. R-T Dozer	0:30	0:47	(Included in backfill)
Remove Upheaval	1. Crawler	0:30	1:00	30 min.
Drift Stockpile	1. R-T Dozer	0:47	1:21	34 min.
	2. Crawler	1:00	1:21	"
Load	1. 1 Loader, (#7) 3 1/2 cy.	0:25	1:21	56 min.
Haul	1. (5) 10-Ton Trucks	0:25	1:25	60 min.
Grade: Cleanup	1. 3 Graders, Runway Road	0:20	0:45	25 min.
	2. 1 Grader, Mat Area	0:45	1:03	18 min.
	3. 1 Grader, Repair Area	1:03	1:30	27 min.
Grade: Level	1. Grader, 1st Cut	1:28	1:40	12 min.
	2. Grader, Finish	1:36	1:48	12 min.
Compact	1. Vibrator A on Sub-Base	1:00	1:15	15 min.
	2. 2 Vibrators Finish	1:21	1:36	15 min.
Sweep	1. 2/3 Rotary Broom	1:15	1:56	41 min.
	2. 2/3 Vacuum	1:15	1:56	"

Equipment Mix A

The debris spoiling by AFR 93-2 equipment uses only the loader since the crawler is utilized for other tasks. Spoiling only the debris on the runway requires 17 minutes, completing at 0:47.

During this time, the crawler completes two tasks; it removes the crater lip in 28 minutes and excavates the crater in 31 minutes, completing at 1:29. Meanwhile, the loader fitted with fork attachment removes the upheaved pavement, finishing at 1:00.

The loader-dozer begins to spoil the excavated soil/debris and removed upheaval, the loader with forks converts to a bucket to assist, and the crawler drifts the temporary stockpile into the excavated crater.

The truck team of five 5-ton trucks requires 280 minutes to haul the required 9950 cubic feet (loose) select fill. The trucks must dump in a temporary stockpile until the crater is completely excavated (at process time 1:29 for the remaining three and one-half hours of hauling, the trucks dump directly into the crater. The crawler can move this stockpile in approximately 106 minutes. This finishes at a process time of 3:16. The loader with forks requires ten minutes to convert to a bucket and help the first loader spoil the excavated material. The two loaders working together finish this task at 3:48.

The stockpile moving thus completes long before the trucks finish at 5:05. In the process of dozing the fill in, the crawler can effect some compaction while placing the fill and leveling that material dumped directly into the crater. The towed compactor cannot be effectively used until the crater depth is less than 4 feet. At a depth of 4 feet, the crater diameter is 30 feet, which allows the towed compactor to turn; but only the outer edge can be compacted. At a depth of about 2 feet the tractor-towed compactor can negotiate the crater laterally, partially due to the crawler-created "ramps." This phase of the process requires close supervision to avoid conflict between the trucks dumping, the crawler filling the crater and the towed compactor. At this stage, the job efficiency will approximate 50 percent, as vehicles are stopped to wait while another completes its cycle.

The final two compaction passes require 30 minutes, followed by 12 minutes of grading as in the AFR 93-2 process. A total process time with AFR 93-2 equipment is 6:25. The task times and equipment assignments are shown in Table 26.

In this process the long haul time of the truck team is not on the critical path. The equipment complement is short of loaders for this approach since the 5-ton trucks incur wait times of 4.8 minutes at the base stockpile for each of 23 loads, or 110 minutes.

Equipment Mix B

For Equipment Mix B, a 3-1/2 cubic yard loader was substituted for the seven 2-1/2 cubic yard loaders of AFR 93-2. Fifteen 10-ton trucks were used instead of fifteen 5-ton trucks. This allows the hauling of select fill to drop from a task time of 280 minutes to 115 minutes, even with one loader for 15 trucks. The larger trucks wait 4.8 minutes per load as before, but since each truck only makes nine loads, the total wait time is 43 minutes.

In this mix of equipment, the spoiling of excavated material and the moving of the temporary stockpile continue past the finish of hauling select fill. This indicates a shortage of dozing/spoiling capability.

The compactor, due to trucks dumping and the crawler drifting fill into the crater, cannot start until the crater is full. It makes two coverages, then the grader makes its first cut. The compactor then makes two more passes before the grader finish cut. The brooms complete 20 minutes after the repair area is clear of other vehicles, finishing at 4:36. The process task times are shown in Table 27 .

<u>Equipment Mix C</u>

Another analysis of the process was made using an excavator similar to the UK film. A rubber-tired dozer was also added; these two vehicles relieve the crawler and increase the dozer capability over Mix B. Two more 3-1/2 cubic yard loaders were added to the base stockpile.

In this analysis, the rubber tired dozer breaks the lip tangentially. The crawler starts immediately on upheaved pavement and debris close to the rim so that the excavator can have access to the crater. One loader spoils debris as in the previous analysis.

This sequence allows the R-T to finish removing the lip in 28 minutes, after which it joins the second loader at spoiling to excavated material. The excavator finishes at 1:13. The crawler completes removal of the upheaved pavement in 30 minutes; it then starts to drift the temporary stockpile into the crater. At 2:46 the crawler joins in spoiling, allowing the tasks to complete at 2:55.

The 10-ton trucks require 98 minutes to haul the select fill. It takes three dozer-type vehicles 124 minutes to doze in this fill. This sequence is still dozer limited. The addition of one more R-T dozer would alleviate this problem, but is only required for the UK large crater process.

Process task times are shown in Table 28 .

LARGE CRATER ADVANCED FILL BDR PROCESS

A study objective was to assess the BDR tasks to support a BDR process which uses an advanced method of filling the crater. Such fill could be cement, plastic, preforms, etc. Since the actual advanced fill process was not a part of this study, the tasks analyzed were:

- Cleanup and spoil
- Optional excavation of crater
- Remove upheaved pavement
- Cleanup small debris.

This eliminated the hauling and placement of select fill. The associated tasks such as compacting and finish grading the fill area are thus not a part of this process analysis.

TABLE 26. U.K. PROCESS
LARGE CRATER EQUIPMENT MIX A

TASK	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. N/A	N/A	N/A	N/A
Spoil	1. Loader A	0:30	0:47	17 min.
Drift Stockpile	1. Crawler	1:30	3:16	106 min.
Remove Lip	1. Crawler	0:30	0:58	28 min.
Remove Upheaval	1. Loader B w/Forks	0:30	1:00	30 min.
Excavate	1. Crawler	0:58	1:29	31 min.
Spoil Excavated	1. Loader A	0:47	3:48	181 min.
	2. Loader B	1:10	3:48	" "
Load	1. 1/3 Loader, (#7) 2 1/2 cy.	0:25	5:01	276 min.
Haul	1. (5) 5-Ton Trucks	0:25	5:05	280 min.
Grade: Cleanup	1. 3 Graders, Runway Road	0:20	0:45	25 min.
	2. Grader, Repair Area	0:45	1:12	27 min.
Grade: Level	1. Grader, 1st Cut	5:35	5:47	12 min.
	2. Grader, Finish	6:05	6:17	12 min.
Compact	1. Vibrator in Crater	3:20	5:00	100 min.
	2. Vibrator on Top Course	5:05	6:05	60 min.
Sweep	1. 2/3 Rotary Broom	1:12	6:25	313 min.
	2. 2/3 Vacuum	1:12	6:25	313 min.

TABLE 27. U.K. PROCESS

LARGE CRATER EQUIPMENT MIX B

TASK	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. N/A	N/A	N/A	N/A
Spoil	1. Loader A	0:30	0:47	17 min.
Drift Stockpile	1. Crawler	1:30	3:16	106 min.
Remove Lip	1. Crawler	0:30	0:58	28 min.
Remove Upheaval	1. Loader B w/Forks	0:30	1:00	30 min.
Excavate	1. Crawler	0:58	1:29	31 min.
Spoil Excavated	1. Loader A	0:47	3:48	181 min.
	2. Loader B	1:10	3:48	"
Load	1. 1/3 Loader, (#7) 3 1/2 cy.	0:25	2:15	110 min.
Haul	1. (5) 10-Ton Trucks	0:25	2:20	115 min.
Grade: Cleanup	1. 3 Graders, Runway Road	0:20	0:45	25 min.
	2. Grader, Repair Area	0:45	1:12	27 min.
Grade : Level	1. Grader, 1st Cut	3:46	3:58	12 min.
	2. Grader, Finish	4:16	4:28	12 min.
Compact	1. Vibrator on Top Course	3:16	3:46	30 min.
	2. Vibrator Finish	3:46	4:16	30 min.
Sweep	1. 2/3 Rotary Broom	1:12	4:36	204 min.
	2. 2/3 Vacuum	1:12	4:36	204 min.

TABLE 28. U.K. PROCESS

LARGE CRATER EQUIPMENT MIX C

TASK	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. N/A	N/A	N/A	N/A
Spoil	1. Loader A	0:30	0:47	17 min.
Drift Stockpile	1. Crawler	1:00	2:46	106 min.
Remove Lip	1. R-T Dozer	0:30	0:58	28 min.
Remove Upheaval	1. Crawler	0:30	1:00	30 min.
Excavate	1. Excavator	0:40	1:13	33 min.
Spoil Excavated	1. Loader B	0:30	2:55	145 min.
	2. R-T Dozer	0:58	2:55	"
Load	1. Loader, 3 1/2 cy.	0:25	1:59	94 min.
Haul	1. (5) 10-Ton Trucks	0:25	1:59	98 min.
Grade: Cleanup:	1. 3 Graders, Runway Road	0:20	0:45	25 min.
	2. Grader, Repair Area	0:45	1:12	27 min.
Grade: Level	1. Grader, 1st Cut	3:16	3:28	12 min.
	2. Grader, Finish	3:46	3:58	12 min.
Compact	1. Vibrator on Top Course	2:46	3:46	60 min.
Sweep	1. Wet Brush	1:12	4:06	174 min.

Equipment Mix A

The crater area is worked initially similar to the UK process: remove lip, spoil all debris and remove upheaved pavement. The crater is not excavated in this approach, due to the increased fill quantities required.

The spoiling of all debris is accomplished by the loader-dozer. The crawler breaks the crater lip while a loader with forks removes upheaved pavement.

The time line for the dozer activities is:

Crawler breaks lip	28 minutes
Loader with forks removes upheaval	30 minutes
Loader spoils debris	17 minutes.

Process task times are shown in Table 29.

Equipment Mix B

The earlier analyses involved changes to reduce hauling times and dozing times. Since there is no defined hauling time here, the only time improvements would be to add more dozers. The guide for Mix B was to substitute equipment in quantities the same as AFR 93-2. Therefore, Mix B will be the same as Mix A. Process task times are shown in Table 29.

Equipment Mix C

Equipment Mix C represents added quantities of equipment to increase effectiveness. Since the longest task time on the Mix A analysis was 30 minutes, only minor time improvements can be made. Considering that 30 minutes is used to deploy equipment, the process time for Mix A of 2 hours and 19 minutes is not unrealistic.

The addition of an R-T dozer would allow faster completion of the lip removing and spoiling tasks. The loader with forks starts removing upheaval and is joined by the crawler at 0:44. The R-T dozer spoils upheaval with the loader-dozer and these tasks finish by 0:57.

The grader and a wet-brush sweeper finish cleanup of the area by 1:22.

Task times for the Advanced Fill process for Mix C are shown in Table 30.

SMALL CRATER REPAIRS - AFR 93-2 PROCESS

The repair sequence for the small craters requires two approaches: One for an open crater and another for camouflet types. As described in Section III, the open crater is typical of a sandy sub-base; the camouflet is more likely in a heavy clay course which is topped with thicker concrete.

For the purposes of this analysis, an average damage condition was developed from test data as described previously. The analysis is based on a runway with 12-inch-thick concrete, with thirty craters spaced 167 feet apart, alternately spaced on opposite sides of the required 54-foot runway (see Figure 21).

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TABLE 29. ADVANCED FILL PROCESS

LARGE CRATER EQUIPMENT MIX A AND B

TASK	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. N/A	N/A	N/A	N/A
Spoil	1. Loader A	0:30	0:47	17 min.
Spoil Upheaval	1. Loader A	0:47	1:17	30 min.
Remove Lip	1. Crawler	0:30	0:58	28 min.
Remove Upheaval	1. Loader B w/ Forks	0:30	1:00	30 min.
Excavate	1. N/A	N/A	N/A	N/A
Load	1. N/A	N/A	N/A	N/A
Haul	1. N/A	N/A	N/A	N/A
Grade: Cleanup	1. 3 Graders, Runway Road 2. Grader, Repair Area	0:20 1:00	0:45 1:27	25 min. 27 min.
Grade: Level	1. N/A	N/A	N/A	N/A
Compact	1. N/A	N/A	N/A	N/A
Sweep	1. 2/3 Rotary Broom 2. 2/3 Vacuum	1:00 1:00	2:19 2:19	79 min. 79 min.

TABLE 30. ADVANCED FILL PROCESS

LARGE CRATER EQUIPMENT MIX C

TASK	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. N/A	N/A	N/A	N/A
Spoil	1. Loader A	0:30	0:47	17 min.
Spoil Upheaval	1. Loader A	0:47	0:57	13 min.
	2. R-T Dozer	0:44	0:57	"
Remove Lip	1. Crawler	0:30	0:44	14 min.
	2. R-T Dozer	0:30	0:44	"
Remove Upheaval	1. Loader B w/Forks	0:30	0:52	22 min.
	2. Crawler	0:44	0:52	"
Excavate	1. N/A	N/A	N/A	N/A
Load	1. N/A	N/A	N/A	N/A
Haul	1. N/A	N/A	N/A	N/A
Grade: Cleanup	1. Grader, 1/3 Runway	0:20	1:00	40 min.
Grade: Level	1. N/A	N/A	N/A	N/A
Compact	1. N/A	N/A	N/A	N/A
Sweep	1. S/P Wet Brush	0:52	1:22	30 min.

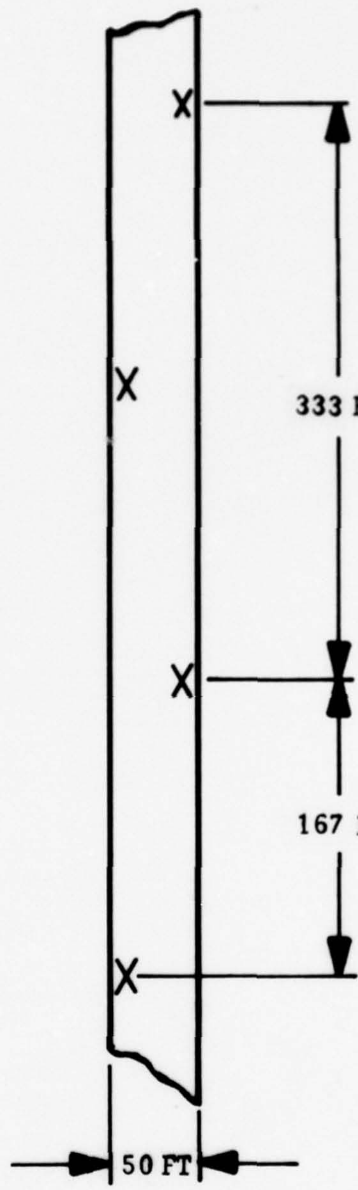


Figure 21. Small Crater Location ~ 30 Craters/5000 ft.

The force deployment is conducted as previously noted for large crater repair; the trucks leave for the base stockpile and the graders clear haul roads on the route for BDR repair.

The overall task approach to the crater repair is as described for large-crater repair: (1) the first repair areas are immediately designated; and (2) spoil areas, mat assembly areas and temporary stockpile locations are selected and marked with portable type guidons/pylons.

The most effective repair method at the 167-foot crater spacing is to work the three crews on three adjacent craters and progress down the runway. This allows the earliest continuous repaired length to be available for takeoff by planes not requiring the full 5000-foot runway length.

For more closely spaced craters, the OIC must select craters far enough apart to avoid traffic congestion, but close enough together to allow coordination of activities.

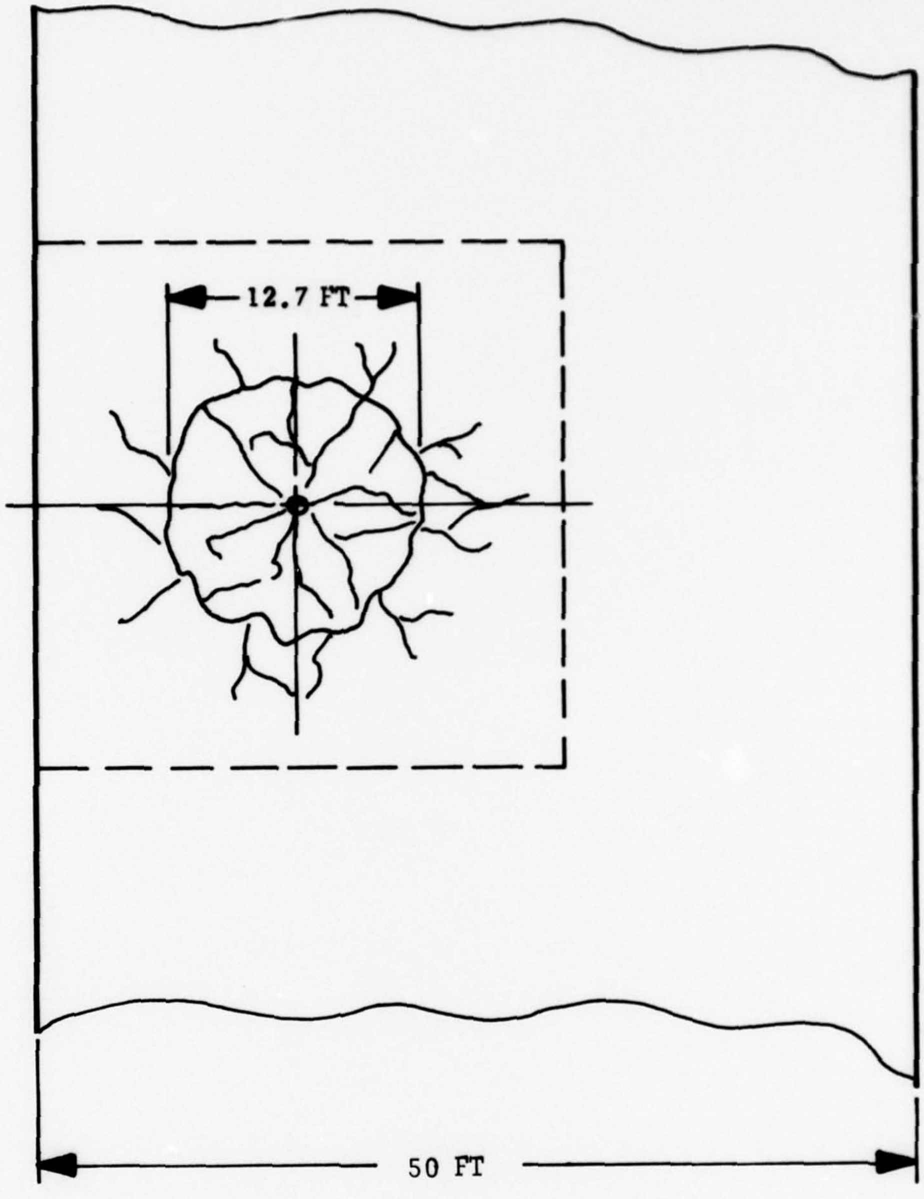
<u>Small Crater - Open Mode</u>

As presented earlier in the discussion of large crater repair, actual repair commences with the backfill and spoil activities for open crater modes. (The camouflet repair problem is discussed later in this section.) The assumed distribution is such that backfilling from 15 feet and inward includes all significant debris. As noted in Section V, the debris population amounts to approximately 375 cubic feet of concrete. The 375 cubic feet (in-place volume) becomes 600 cubic feet loose (1.6 bulking factor); however, the small crater volume in sand is only 220 cubic feet, disregarding upheaved pavement. This situation requires spoiling some debris to avoid overfilling the crater. Since the soil ejecta is useful for fill, the larger pieces should be spoiled. Backfilling from about 4 feet inward will supply up to 190 cubic feet (loose) and is considered more than adequate debris fill. (The small crater repairs require close supervision to avoid overfilling and/or projecting debris corners that interfere with compaction, grading, and capping. The crawler can backfill this quantity in 4 minutes.

The time required to spoil all blown-out debris is 11 minutes for a single dozer, 6 minutes for two dozers. Since each repair team must repair 10 craters in this analysis, then for the case where both dozer-type vehicles spoil continuously, 60 minutes is required just to clear the runway of loose debris. Using the backfill method, the loader requires 7 minutes per crater for spoiling.

In addition to debris spoiling, work also includes handling a maximum of 525 square feet of upheaved concrete for each crater area repair. This upheaval must be removed and spoiled. As indicated in Section III, the damage reports indicate the average total pavement repair area is 426 square feet (for the open crater). Thus, for this analysis, only 51 square feet of additional pavement will require removal.

From Figure 22, up to four runway sections per crater may require removal. The blast-induced cracking assumed for this study will normally result in about four or five concrete pieces per slab, with four slabs requiring approximately 27 minutes to remove. Spoiling these pieces requires another



REQUIRES REPLACEMENT OF FOUR SLABS

Figure 22. Small Crater~Worst Case Damage

27 minutes, however, the spoil time is almost concurrent with the removal time when another vehicle is available. For the pavement removal average quantity of 51 square feet (approximately four pieces), the loader required six minutes.

The dozer with blade works more effectively on the open crater than in a camouflet since some debris can be pushed in and used as support. The dozer should work continuously on one crater, finishing all upheaved-concrete removal, before going to another crater. Since all of the vehicles analyzed can spoil the largest pieces, a second vehicle can accomplish spoiling while the dozer removes upheaval.

The crawler backfills from approximately 4 feet to fill the crater to within one foot of being flush with the undisturbed pavement. This requires 4 minutes. The loader with forks removes upheaved pavement, completing that task in 27 minutes for the worst case.

The loader-dozer spoils the debris not used for backfill in 7 minutes, then spoils the upheaved pavement removed by the crawler. This task ends at 0:46 with the help of the crawler.

Since the small open crater requires a total select fill of 539 cubic feet for the crater and removed concrete in the backfill method, the 5-ton trucks dump six 3.2 cubic yard loads at each crater site. In 17 minutes they can supply the fill for a single crater (at 0:42). Since the crawler is occupied until 0:46, the trucks would have to wait to dump into the crater. Dumping can begin when the crawler has finished the backfill task, but only one or two truckloads. The dozer can spread the dumped material while it is maneuvering to remove upheaval.

Since the compaction and grading tasks are the same for both cratering models, the debris handling and crater fill operations for the camouflet mode will be presented in the following sections.

Equipment Mix B

The equipment in Mix A finished the tasks prior to compaction and cleanup by 0:46. For ten craters, this would require 160 minutes plus the 30 minutes deployment time. Substitution for Mix B would not significantly reduce this time, since Mix B uses the same quantities of equipment as Mix A. Process task times for Mixes A and B are shown in Table 31.

Equipment Mix C

Equipment Mix C uses additional pieces of equipment to improve task times. For the small craters, an added dozer at the crater and two additional loaders at the base stockpile will improve 10 crater performance.

One item considered was a dozer with ripper. A dozer with only a ripper is at a disadvantage in the open crater: The dozer is positioned on the pieces it is trying to remove; thus it breaks up the slab into smaller pieces which then require additional time for removal. Ripping, especially in 12-inch concrete, requires a heavy dozer of the Caterpillar D8 class. As an estimate, the dozer-ripper requires 22 minutes to remove 375 square feet of upheaval in the open crater mode; about 6 minutes for the 51 square feet upheaval in the open crater mode; about 6 minutes for the 51 square feet of this camouflet analysis.

TABLE 31. AFR 93-2 PROCESS

SINGLE SMALL CRATER EQUIPMENT MIX A

TASK	EQUIPMENT	TIME START	TIME COMPLETE	START TIME
Backfill	1. Crawler	0:30	0:34	4 min.
Spoil	1. Loader A	0:30	0:37	7 min.
Spoil Upheaval	1. Crawler	0:34	0:46	9 min.
	2. Loader A	0:37	0:46	"
Remove Lip	1. Crawler	0:30	0:34	(Included in backfill)
Remove Upheaval	1. Loader B w/Forks	0:30	0:36	6 min.
Excavate	1. N/A	N/A	N/A	N/A
Load	1. 1/3 Loader #7	0:25	0:41	16 min.
Haul	1. (5) 5-Ton Trucks	0:25	0:45	20 min.
Grade: Cleanup	1. 3 Graders, Runway Road	0:20	0:45	25 min.
	2. Grader, Mat Area	0:45	0:54	9 min.
	3. Grader, Repair Area	1:01	1:07	6 min.
Grade: Level	1. Grader, 1st Cut	0:55	1:01	6 min.
	2. Grader, Finish	1:13	1:19	6 min.
Compact	1. Vib. Roller, 1st cover	0:45	0:55	10 min.
	2. Vib. Roller, 2nd cover	1:01	1:13	12 min.
Sweep	1. 2/3 Rotary Broom	1:07	1:25	18 min.
	2. 2/3 Vacuum	1:07	1:25	18 min.

Small Crater-Camouflet Mode

From the damage prediction data of Section III, the camouflet mode produces a roughly spherical crater below the runway surface. Little concrete area is actually blown out; usually a small vent hole of about 12-inch-diameter is found. Pavement repair area averages 750 square feet in the camouflet mode.

This small opening requires some ripping or excavating to gain access to the lower crater. The task of "opening up" the camouflet crater can be accomplished by a loader with (1) a fork attachment, (2) a heavy crawler with single ripper tooth, or (3) an excavator/ backhoe vehicle. A dozer with a straight blade is not effective, since the operator cannot get the corner of the blade angled effectively into the small hole and/or radial cracks produced by the small penetrator charges.

For a repair team without an excavator, such as the AFM 93-2 team, the loader with fork attachments will have to angle the forks down and dig the crater open.

For the backfill crater filling task, the camouflet requires 23 cubic yards of fill, including the removed pavement volume after the vent hole material falls back. Using all debris for backfill will provide 600 cubic feet (loose) in the crater. This will be a little too full to allow satisfactory compaction. Using only the debris within 10 feet of the crater lip will use the larger pieces and require 92 cubic feet loose of fill dirt, or one heaped 5-ton truckload.

Backfilling the crater requires 4 minutes for the crawler. The trucks can deliver the fill and wait at the crater with this task time. Each truck requires approximately 6.75 minutes for a complete cycle (load, haul, spot, dump and return); if the truck waits at the crater, an additional waiting time is added into the cycle. This is variable Q2 in the Truck Team Hauling Program (Appendix C).

The loader with forks requires 15 minutes to open the crater vent and another 15 minutes to remove the additional upheaved pavement. In this approach, the crawler spoils the removed upheaval with the loader-dozer.

Since the haul cycle is not penalized by waiting trucks (i.e., nothing to gain by stockpiling), the trucks can wait until the crater is ready for select fill at 1:00. If the trucks stockpile, the crawler has to spread that material into the crater which extends the required crawler time. The spoiling of upheaval is constrained by the loader removing the pavement.

Compaction and Grading - Small Craters

Compaction is accomplished by four passes of the vibratory roller over the select fill. The sequence involves the following steps:

1. Overfilling the crater.
2. Compacting across twice in one direction.
3. Grader leveling.
4. Compating two coverages at 90 degrees to the first direction.
5. Finish grading.

The above-listed sequence uses the following times:

1. Compact, two coverages   10 minutes
2. Grader level   6 minutes

3.	Compact, two coverages	12 minutes
4.	Grader finish	6 minutes
		34 minutes

The subsequent finish sweeping task requires seven minutes per crater, completing the open crater repair at 1:25. The sweeper has previously swept runway areas away from the crater. **Process Task times are shown in Table 32.**

Equipment Mix B

As in the small open crater, no advantage is gained by equipment substitutions. The work quantities are small and the travel distances are short. Therefore, bigger, faster machines are little improvement.

Equipment Mix C

As an alternate to upheaval removal with a dozer or loader with forks, an excavator or backhoe could be used; this equipment works well on small pieces. However, a larger vehicle is required to handle the maximum sizes that may be encountered. A vehicle in the 15- to 20-ton class is required. Most excavators of this class are tracked; however, a rubber-tired vehicle is recommended for BDR to facilitate its deployment without additional tractor-trailers. The excavator requires 18 minutes to remove upheaval in the worst case; the average crater will require five minutes.

An excavator can average one swing per minute at digging soil. The accuracy required for pulling upheaved concrete chunks away from the vent will reduce this time, however, because a reduced swing is used. Therefore, an average of one dig per minute is used for this analysis.

Even when the upheaved pavement is pulled back, the small vent hole still does not allow backfill or complete access to the main spherical cavity. Therefore, additional digging is required. An excavator is the best tool for this task, since it can invert the hoe and ram it into the vent, thus collapsing the soil into the cavity. This operation should require only 2-3 minutes, at which time the crater is exposed for subsequent backfill or excavation. This approach, which collapses approximately 5 cubic yards into the crater, is faster than trying to excavate the cylindrical opening.

The total repair time required is one hour and 31 minutes, of which 30 minutes is deployment time. On a ten crater basis per team, the loaders, crawlers and excavator can move to the next crater prior to completion of the first small crater. This allows work to be improved over the first estimate of 10 hours and 20 minutes per ten craters. An additional compactor per team will allow working two compactions at approximately the same time.

Task times for the process are shown in Tables **33** and **34**.

SMALL CRATERS - UK PROCESS

For the UK process, all debris is spoiled. In addition, any crater debris or plastically deformed material must be removed from the crater; this is almost impossible for a loader or dozer. The small diameter of the crater does not allow sufficient access and working room. The dozer could cut a ramp into the crater and work the task, but this creates additional crater

TABLE 32. AFR 93-2 PROCESS

SINGLE SMALL OPEN CRATER EQUIPMENT MIX C

TASK	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. Crawler	0:30	0:34	4 min.
Spoil including Upheaval	1. Loader A	0:30	0:40	10 min.
	2. Loader B	0:30	0:40	"
	3. Crawler	0:34	0:40	"
Remove Lip	1. Crawler	0:30	0:34	(Included in backfill)
Remove Upheaval	1. Excavator	0:30	0:35	5 min.
Excavate	1. N/A	N/A	N/A	N/A
Load	1. Loader	0:25	0:33	8 min.
Haul	1. (5) 10-Ton Trucks	0:25	0:37	12 min.
Grade: Cleanup	1. 3 Graders, Runway Road	0:20	0:45	25 min.
	2. Grader, Mat Area	0:45	0:54	9 min.
	3. Grader, Repair Area	1:00	1:06	6 min.
Grade: Level	1. Grader, 1st Cut	0:54	1:00	6 min.
	2. Grader, Finish	1:13	1:19	6 min.
Compact	1. S/P Vib. Roller 1st cover	0:37	0:47	10 min.
	2. Vib. Roller, 2nd cover	1:00	1:12	12 min.
Sweep	1. S/P Wet Brush	1:18	1:25	7 min.

TABLE 33. AFR 93-2 PROCESS

SINGLE SMALL CRATER EQUIPMENT MIX A

TASK	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. Crawler	0:35	0:39	4 min.
Spoil	1. Loader A	0:30	0:37	7 min.
Spoil Upheaval	1. Loader A	0:37	1:02	25 min.
	2. Crawler	0:39	1:02	"
Open Vent	1. Loader w/Forks	0:30	0:45	15 min.
Remove Upheaval	1. Loader w/Forks	0:45	1:00	15 min.
Excavate	1. N/A	N/A	N/A	N/A
Load	1. 1/3 Loader #7	0:25	0:33	8 min.
Haul	1. (5) 5-Ton Trucks	0:25	1:02	37 min. (Includes 25 min. wait at crater)
Grade: Cleanup	1. 3 Graders, Runway Road	0:20	0:45	25 min.
	2. Grader, Mat Area	0:45	0:54	9 min.
	3. Grader, Reapir Area	0:54	1:00	6 min.
Grade: Level	1. Grader, 1st Cut	1:12	1:18	6 min.
	2. Grader Finish	1:30	1:36	6 min.
Compact	1. Vib. Roller, 1st cover	1:02	1:12	10 min.
	2. Vib. Roller, 2nd cover	1:18	1:30	12 min.
Sweep	1. 2/3 Rotary Broom	1:36	1:43	7 min.
	2. 2/3 Vacuum	1:36	1:43	7 min.

TABLE 34. AFR 93-2 PROCESS

SMALL CAMOUFLET CRATER EQUIPMENT MIX C

TASK	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. Crawler	0:43	0:47	4 min.
Spoil including Upheaval	1. Loader A	0:30	0:45	15 min.
	2. Loader B	0:30	0:45	"
Open Vent	1. Excavator	0:30	0:38	8 min.
Remove Upheaval	1. Excavator	0:38	0:43	5 min.
Excavate	1. N/A	N/A	N/A	N/A
Load	1. Loader, 3 1/2 cy.	0:25	0:33	8 min.
Haul	1. (5) 10-Ton Trucks	0:25	0:49	24 min.
Grade: Cleanup	1. 3 Graders, Runway Road	0:20	0:45	25 min.
	2. Grader, Mat Area	0:45	0:54	9 min.
	3. Grader, Repair Area	0:54	1:00	6 min.
Grade: Level	1. Grader, 1st Cut	1:00	1:06	6 min.
	2. Grader, Finish	1:18	1:24	6 min.
Compact	1. S/P Vib. Roller, 1st cover	0:49	0:59	10 min.
	2. S/P Vib. Roller, 2nd cover	1:06	1:18	12 min.
Sweep	1. S/P Wet Brush	1:24	1:31	7 min.

repair work for an already fully involved repair team. Therefore, an excavator appears to be required for this method and will be used instead of a crawler for Equipment Mix A.

An excavator with a one-cubic-yard bucket can excavate the 189 cubic feet of crater fallback and deformed material in seven swings (or about 7 minutes total). A loader can subsequently spoil this excavated material in 10 minutes.

The excavator first opens the vent hole in five minutes, then expands the vent hole to expose the crater in another three minutes. After the seven minutes required to excavate, the machine then removes upheaved pavement for 13 minutes, finishing these tasks at (T_O + 56).

The loaders can be fitted with the four-in-one bucket if an excavator is available. This allows the loaders to spoil all debris by 0:53.

The five 5-ton trucks deliver two loads each to the small camouflet crater, for a total of 890 cubic feet. Because this is slightly more than required, the last two loads should be dumped under close supervision. The two minutes required for each truck in queue to spot and dump allows a truck to make another cycle first as the queue disappears. The task would require approximately 15 minutes without waiting; by the queue method it finishes at 1:11.

Compaction is as in the AFR 93-2 process. The sweeping task again takes 7 minutes per crater, thus the crater repair finishes at 1:40. Process task times are shown in Table 35 .

Equipment Mix B

Since a substitution had to be made in Mix A to allow excavation, no further change is required for Mix B except to use a 3-1/2 cubic yard loader and five 10-ton trucks, which only make one load each to the crater. This reduces the time to 1:34, as shown in Table 36.

Equipment Mix C

For equipment Mix C, the crawler is added back into the team. This allows faster spoiling and allows an earlier start to compaction. If two rollers are used, 11 minutes are saved on the process time in compaction. Task times for this mix are in Table 37 .

UK Summary

The times per crater for open or camouflet are so similar that the task times for a UK process repair on camouflet were not differentiated. Since an excavator was used on the AFR 93-2 repair of camouflets, the task times relating to opening the vent are similar. After that the sequence follows the open crater repair process.

SMALL CRATERS - ADVANCED FILL PROCESS

The Advanced Fill Process includes spoiling all debris, but does not include excavation of the crater.

The excavator or loader with forks opens the vent and expands the crater (as described above for the AFR 93-2 and UK processes). The equipment used

TABLE 35. U.K. PROCESS

SMALL OPEN CRATER EQUIPMENT MIX A

TASK	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. N/A	N/A	N/A	N/A
Spoil	1. Loader A	0:30	0:37	7 min.
Spoil Upheaval	1. Loader B	0:37	0:53	16 min.
Remove Lip	1. Excavator	0:30	0:37	7 min. (Included in excavate)
Remove Upheaval	1. Excavator	0:37	0:50	13 min.
Excavate	1. Excavator	0:30	0:37	7 min.
Spoil Excavate	1. Loader A	0:37	0:47	10 min.
Load	1. 1/3 Loader, 2 1/2 cy.	0:25	0:49	24 min.
Haul	1. (5) 5- Ton trucks	0:25	1:11	46 min.
Grade: Cleanup	1. 3 Graders, Runway Road 2. Grader, Repair Area	0:20 0:45	0:45 0:51	25 min. 6 min.
Grade: Level	1. Grader, 1st Cut 2. Grader, 2nd Cut	1:21 1:33	1:27 1:39	6 min. 6 min.
Compact	1. Vib. Rollers 1st cover 2. Vib. Rollers 2nd cover	1:11 1:21	1:21 1:33	10 min. 12 min.
Sweep	1. 2/3 Rotary Broom 2. 2/3 Vacuum	1:33 1:33	1:40 1:40	7 min. 7 min.

TABLE 36. U.K. PROCESS

SMALL OPEN CRATER EQUIPMENT MIX B

TASK	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. N/A	N/A	N/A	N/A
Spoil	1. Loader A	0:30	0:37	7 min.
Spoil Upheaval	1. Loader B	0:37	0:53	16 min.
Remove Lip	1. Excavator	0:30	0:37	7 min. (Included in excavate)
Remove Upheaval	1. Excavator	0:37	0:50	13min.
Excavate	1. Excavator	0:30	0:37	7 min.
Spoil Excavate	1. Loader A	0:37	0:47	10 min.
Load	1. 1/3 Loader	0:25	0:37	12 min.
Haul	1. (5) 10-Ton Trucks	0:25	0:41	16 min.
Grade: Cleanup	1. 3 Graders, Runway Road	0:20	0:45	25 min.
	2. Grader, Repair Area	0:45	0:51	6 min.
Grade: Level	1. Grader, 1st Cut	1:03	1:09	6 min.
	2. Grader, Finish	1:21	1:27	6 min.
Compact	1. Vib. Roller, 1st cover	0:53	1:03	10 min.
	2. Vib. Roller, 2nd cover	1:09	1:21	12 min.
Sweep	1. 2/3 Rotary Broom	1:27	1:34	7 min.
	2. 2/3 Vacuum	1:27	1:34	"

TABLE 37. U.K. PROCESS

SINGLE SMALL OPEN CRATER EQUIPMENT MIX C

TASK	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. N/A	N/A	N/A	N/A
Spoil	1. Loader A	0:30	0:37	7 min.
Spoil Upheaval	1. Loader A	0:37	0:53	16 min.
Remove Lip	1. Excavator	0:30	0:37	7 min. (Included in excavate)
Remove Upheaval	1. Excavator	0:37	0:50	13 min.
Excavate	1. Excavator	0:30	0:37	7 min.
Spoil Excavate	1. Crawler	0:30	0:40	10 min.
Load	1. Loader, 3 1/2 cy.	0:25	0:29	4 min.
Haul	1. (5) 10-Ton Trucks	0:25	0:41	16 min.
Grade: Cleanup	1. 3 Graders, Runway Road	0:20	0:45	25 min.
	2. Grader, Repair Area	0:45	0:51	6 min.
Grade: Level	1. Grader, 1st Cut	0:58	1:04	6 min.
	2. Grader, Finish	1:10	1:16	6 min.
Compact	1. 2 Rollers, 1st cover	0:53	0:58	5 min.
	2. 2 Rollers, Finish	1:04	1:10	6 min.
Sweep	1. S/P Wet Brush	1:16	1:23	7 min.

in the mix then removes upheaved pavement; all three tasks require a total of 13 minutes. The loader and crawler spoil all debris, including the removed upheaval, in 11 minutes, by 0:41.

The grader and sweeper also work as in previous processes, resulting in a total process time of 2 hours and 4 minutes, including the 30 minutes to assemble, deploy and survey prior to start of the repair. Graders and sweepers are constrained to completion times which follow all other tasks. Therefore, in all these analyses the grading and sweeping tasks vary, depending upon the progress of work in other tasks.

The time presented for the first crater can be slightly improved on subsequent craters. The excavator and loader can move to the next crater. Therefore, work can be done on the next crater that is not in the critical time line.

As in the other small crater repair processes, time is so similar between open and camouflet that only the open crater repair times are shown in Tables 38, 39, and 40.

One suggested method of improving the ten-crater timeline is:

1. Add extra dozers and compactors to the equipment complement.
2. Have the trucks dump while the excavator is removing upheaval (requiring particularly close direction of work patterns near the crater lip).

TIME VERSUS QUALITY TRADEOFFS

The time required to perform any of the BDR unit operations, tasks, or complete processes must be assessed in terms of when to terminate that process. Beyond some degree of quality, any further effort is inefficient and, in some processes, detrimental to the desired result. The difficult task for an earthwork supervisor is to determine that tradeoff point.

Construction supervisors such as civilian "dirt foremen" develop an experience level through many years of earthwork. In addition, their judgment is periodically referenced to instrumentation results from soil penetrometers, load plates, and level sightings. The use of such instruments is required because of the non-homogeneity of soils. The mix of silt, clay and sand in soil samples may vary considerably within a few feet of consecutive samples. Moisture content, density and the proportion of fines all add further complexity to defining an ideal process time for earthwork.

This study has approached the topic in terms of minimum/maximum quantities of work for a task which allow the successive tasks to be accomplished properly, while minimizing the total process time. The "quality" rationale for establishing these times and quantities is described for each task in the following paragraphs.

Backfilling with Debris vs. Spoiling

Backfilling the crater with nearby debris does not appear to have any quality requirements: i.e., the more backfill obtained near the crater, the less material required to be hauled in for fill.

TABLE 38. ADVANCED FILL PROCESS
SMALL OPEN CRATER EQUIPMENT MIX A

TASK	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. N/A	N/A	N/A	N/A
Spoil	1. Loader	0:30	0:41	11 min.
Spoil Upheaval	1. Crawler	0:34	0:40	6 min.
Remove Lip	1. Crawler	0:30	0:34	4 min.
Remove Upheaval	1. Loader w/Forks	0:30	0:36	6 min.
Excavate	1. N/A	N/A	N/A	N/A
Load	1. N/A	N/A	N/A	N/A
Haul	1. N/A	N/A	N/A	N/A
Grade: Cleanup	1. Grader, 1/3 Runway	0:20	1:00	40 min. (10 craters)
Grade: Level	1. N/A	N/A	N/A	N/A
Compact	1. N/A	N/A	N/A	N/A
Sweep	1. 2/3 Rotary Broom 2. 2/3 Vacuum	0:45 0:45	2:04 2:04	79 min. 79 min. (10 craters)

TABLE 39. ADVANCED FILL PROCESS

SMALL OPEN CRATER EQUIPMENT MIX B

TASK	EQUIPMENT	TIME START	TIME COMPLETE	TASK TIME
Backfill	1. N/A	N/A	N/A	N/A
Spoil	1. Loader A	0:30	0:41	11 min.
Spoil Upheaval	1. Crawler	0:34	0:40	6 min.
Remove Lip	1. Crawler	0:30	0:34	4 min.
Remove Upheaval	1. Loader w/Forks B	0:30	0:36	6 min.
Excavate	1. N/A	N/A	N/A	N/A
Load	1. N/A	N/A	N/A	N/A
Haul	1. N/A	N/A	N/A	N/A
Grade: Cleanup	1. Grader, 1/3 Runway	0:20	1:00	40 min. (10 craters)
Grade: Level	1. N/A	N/A	N/A	N/A
Compact	1. N/A	N/A	N/A	N/A
Sweep	1. 2/3 Rotary Broom 2. 2/3 Vacuum	0:45 0:45	2:04 2:04	79 min. 79 min. (10 craters)

TABLE 40. ADVANCED FILL PROCESS

SMALL OPEN CRATER EQUIPMENT MIX C

TASK	EQUIPMENT	TIME START	TIME COMPLETE	START TIME
Backfill	1. N/A	N/A	N/A	N/A
Spoil	1. Loader A	0:30	0:41	11 min.
Spoil Upheaval	1. Crawler	0:34	0:40	6 min.
Remove Lip	1. Crawler	0:30	0:34	4 min.
Remove Upheaval	1. Loader B w/Forks	0:30	0:36	6 min.
Excavate	1. N/A	N/A	N/A	N/A
Load	1. N/A	N/A	N/A	N/A
Haul	1. N/A	N/A	N/A	N/A
Grade: Cleanup	1. Grader, 1/3 Runway	0:20	1:00	40 min.
Grade: Level	1. N/A	N/A	N/A	N/A
Compact	1. N/A	N/A	N/A	N/A
Sweep	1. S/P Wet Brush	0:45	1:07	22 min.

The theory is subject to three constraints:

1. Spoiling oversized blocks of concrete, instead of using as backfill.
2. Overfilling with debris and/or ejecta is avoided.
3. Minimizing the use of far flung debris.

Spoiling Oversize Blocks. The constraint of spoiling oversized blocks derives from the high probability of large blocks reposing in diagonal or bridging positions in the crater. This creates a problem in filling and compacting the upper crater volume. In this context, blocks on the order of 10 feet square and larger should be spoiled. (Jackhammering them into smaller blocks is possible, but usually causes more confusion and congestion than the gain in fill material warrants.) Using the assumed distribution of debris sizes, the larger sizes are closest to the crater, and may have fallen back into the crater.

In the large craters, where blocks as large as 13 feet square may repose on the crater wall, an attempt should be made to move them to an anchored position near the bottom.

Avoiding Overfilling. The constraint to not overfill the crater is obvious, since the grading and compacting activities cannot be accomplished with high quality with concrete pieces/corners projecting above the earth fill. Ideally, debris should be backfilled only to within 4 or 5 feet of the original top surface of the runway. This height allows better control of compaction depth and ultimate compacted density; however, the requirement for additional fill to be hauled further stresses the truck teams. The AFR 93-2 process calls for backfill to within one foot of grade. This leaves little margin for error in compaction and grading, since a 10 percent settlement is 1.2 inches.

Spoiling Far-Flung Debris. The cycle time required to retrieve far-flung debris is greater than its value as backfill. The pieces beyond approximately 60 feet from the crater are small, on the order of 6 to 12 inches square. Collecting and dozing these pieces further reduces their size and creates additional sweeping work. It is more efficient to add select fill and not retrieve these small fragments.

Spoiling does require a moderate degree of quality in terms of percentage of debris spoiled as a dozer task because the final spoil quality must be high (i.e., not much debris left on runway) to avoid problems with the sweepers. Final spoiling can be accomplished by a grader, if the remaining debris is small.

Breaking the Crater Lip

The only concern in breaking the crater lip is to avoid creating additional work in another task. For a backfill repair process, the crater lip can be broken into the crater. Therefore, in the upheaval task, the only concern is that the crawler does not cause further damage to the pavement with its track cleats.

When the crater is to be excavated, moderate care should be taken to not push the lip into the crater. A cut taken tangential to the rim will deposit a minimum in the crater, although more cuts are required than on the backfill method.

Removing Upheaved Pavement

The July 1974 issue of AFR 93-2 does not have a specific critierion for identifying upheaved pavement. Studies are currently being made of present-day aircraft requirements in terms of tolerable runway discontinuities. Obviously, no more material should be removed than necessary since a 15-foot-square slab requires 250 cubic feet of loose fill to replace it. This is almost three 5-ton truckloads. The upheaval removal time per square foot is discussed in Section VII. The required runway surface levelness to be established will determine what pavement must be removed; the quality must be 100 percent of that requirement.

Placing Select Fill

The placing of select fill requires little extra time to achieve uniform placement, which is the "quality" requirement. Even when dumped from the crater rim by the trucks, the crawler can distribute the fill during its other tasks. Where the select fill is dozed in from a temporary stockpile, the dozer can place it with better quality.

Since the ejected soil is backfilled along with the concrete debris, an additional "quality" requirement is of concern in the backfill of debris processes; the ejecta should be placed into the voids created by the irregular concrete debris. This reduces chances of the debris shifting and causing settlement of the repaired surface. Proper spotting by the haul truck and distribution of the select fill by the dozer will improve necessary quality with little extra time.

Compacting

As discussed in Section VII, compaction can be overdone in some fill materials, especially by a rubber-tired roller. The finished CBR is usually proportional to the number of coverages at a constant moisture content. In addition, full strength is developed by a curing time in which moisture evaporates or migrates from the surface. Where moisture content is difficult to control, best results are achieved when the material is wet of optimum, not dry.

Best compaction results are achieved in numerous uniform shallow lifts of fill material rather than on deep fills. This requires more time in placing the fill, as trucks either wait or dump in a stockpile which in turn requires more dozing time.

The tradeoff is taken to be a one-foot lift with four coverages as the minimum compaction. Each 5-foot-wide pass requires about two minutes on the large craters and one minute on the small craters. In the UK or Spoil and Fill processes, it is difficult to compact more than 2 feet below the normal runway surface due to problems in getting the compactor in and out of the crater. In the small craters, there is not any room for a compactor in the crater. This was the basis for establishing a one-foot lift as a reasonable trade between time, quality and feasibility.

Grading

The grading quality required depends upon the final surface to be used for the expedient runway. If the cap is a formed-in-place material such as regulated-setting cement or a resin, then the final grade on the fill is not critical. The cap material will fill any irregularities and small holes. However, if the runway surface is to be a mat assembly or other prefabricated cap structure, the required grading quality is medium. The graded surface will be gouged by the mat assembly as it is slid into place.

If the runway surface is to be the compacted fill surface, or the fill covered only by a flexible membrane, the grading requirement is the highest. The requirements for runway irregularities will ultimately establish how much unevenness and/or transition changes can be allowed for the graded surface. If the final surface is well-compacted and slightly overfilled, the graders can finish the surface with two light-cut coverages.

The initial grader task of clearing haul roads is of importance to avoid small, sharp rubble from causing truck tire blowouts. This quality can be achieved at normal road maintenance speeds, with some care used to avoid large pieces of debris. (Any large pieces can be removed by the loaders during their deployment to the craters.)

Sweeping

Sweeping quality is critical to a runway used for jet aircraft, due to the possible engine damage from small debris and coarse dust.

This requirement makes the towed rotary brooms used in AFR 93-2 ineffective sweepers. Not only are they a traffic problem, they require two men to operate the broom and towing vehicle. In addition, this type of broom does not collect debris or dust, it merely windrows it. Circular sweeping passes move the windrow off the runway; however, any wind can cause a severe dust problem both for visibility and for rescattering the dust.

The rotating wet brush sweepers commonly seen on street cleaners provide a better quality of sweeping and are self-propelled. The most effective use of this type is to sweep only after all debris is spoiled off the runway so that the sweeper contends only with dust and small gravel.

A vacuum sweeper is effective on dust, but has a problem with hard-packed dirt clods which are left by the truck and dozer traffic patterns. In wet weather, the vacuum can become clogged with wet mud.

In lieu of a specific definition of "swept quality" for an expedient runway, the conclusion drawn is that the sweeping time noted previously for the repair problem is the minimum time for a marginally adequate sweep under ideal (dry) conditions; increasing the time under any other than the ideal dry conditions will not improve the quality.

The next section discusses equipment changes, equipment modifications and new techniques for improved BDR process times.

SECTION IX

EQUIPMENT MODIFICATION CONCEPTS

One of the study objectives was to develop concepts for equipment modifications which would reduce the BDR time to 2 hours, with a 1 hour repair time as the ultimate goal.

The equipment modifications to be considered were structured into four categories:

1. Currently-available U.S. manufactured items usable as produced.
2. Equipment usable with minor modifications (cost of modification not to exceed 10 percent of the original equipment cost).
3. Equipment usable with major modifications, dedicated to BDR.
4. New conceptual equipment, dedicated to BDR.

The results of the study as related to each of these four categories is discussed in this section.

CURRENT PRODUCTION EQUIPMENT

Among the BDR applicable items of equipment which are currently in production and which are not authorized by AFR 93-2 are:

1. Larger trucks and loaders
2. Road planners
3. Concrete saws
4. Excavator/backhoes
5. Rubber-tired dozers (available in a range of sizes)
6. Vibratory compactors
7. Pneumatic compactors.

The analyses of the three BDR processes highlighted several high-time tasks which could be reduced by either changing equipment or adding equipment to the AFR 93-2 list.

Rubber-Tired Dozers and Larger Trucks

In the large crater AFR 93-2 analysis, the process was dozer-limited; that is, the dozer tasks paced the repair time prior to compaction. Adding two rubber-tired dozers resolved this problem, but now the process was truck limited.

The analysis of the UK process showed the method was initially truck-limited due to the increase requirement for hauling fill.

Because of these observations, a fleet of 10-ton trucks was analyzed for the two hauling task process. The comparative times on large craters are recapitulated in Table 41.

TABLE 41. 5-TON TRUCKS COMPARED TO 10-TON TRUCKS

Process	5-Ton Haul Time	10-Ton Haul Time
AFR 93-2	83 minutes	43 minutes
UK	178 minutes	98 minutes

On this basis, the fifteen 5-ton trucks should be replaced by fifteen 10-ton trucks.

Larger Loaders

The current AFR 93-2 bucket loaders use a 2 1/2 cubic yard bucket, which is a mismatch for 5-ton trucks. The 5-ton trucks haul approximately 3.2 cubic yards per load. This means that either the loader uses two cycles to load each truck, or that the truck leaves with a "short" load from one loader cycle. A 3 1/2 cubic yard bucket, available for loaders that develop greater than 15,000 pounds breakout force, would fill a 5-ton truck in one cycle and a 10-ton truck in two cycles. The tipping load at maximum articulation angle for this class of loaders is approximately 7000 pounds, which requires that the loaded bucket be kept low during sharp turns and direction changes. (The low bucket position is a normal position in the most efficient Y-pattern cycle.)

Excavators and Dozers for Upheavel

The AFR 93-2 process time was improved by adding two rubber-tired dozers to assist in spoiling, backfilling and removing upheaved pavement. The rubber-tired type was recommended for ease of deployment, since they can drive to the repair area and do not require a tractor-trailer to deliver them. In the case of BDR, which must be accomplished in any weather, the crawler dozer should be retained for its high mobility in wet ground.

The UK and Advanced Fill process were not as severely dozer-limited. In the UK process, however, the requirement for excavating the crater resulted in the addition of a large rubber-tired excavator. This excavator can then remove upheaved pavement as well. Accordingly, only one rubber-tired dozer is added to those process teams.

Compactors

The AFR 93-2 BDR equipment roster includes three towed vibratory rollers (one for each crater team in this analysis). The minimum final compaction effort requires 30 minutes for a single compactor. The revised equipment lists which were considered used two compactors, both self-propelled vibratory rollers. A more flexible complement of equipment would have one vibratory and one pneumatic roller. An adequate pneumatic roller would be a nine-tire self-propelled vehicle weighing over 20,000 pounds.

The use of self-propelled vehicles is advised for logistic reasons because no support vehicle is required for either deployment over short distances or for work activities.

Road Planer

During tha analysis of upheaved pavement, the use of a road planer such as the new Galion RP-30 was considered. The road planer resembles a grader fitted with a revolving drum which has carbide spikes. The drum shaves particles from uneven surfaces for leveling and can be used to remove roadways, etc. For BDR, it was examined for application to level upheaved pavement. The conclusions arrived at were:

1. The planer creates a significant volume of chips and dust, which would require dozing or grading and sweeping.
2. An upheaved slab may not be firm enough, even if leveled, to support repetitive traffic loads.

Concrete Saws

Concrete saw are available which could be used to reduce upheaved concrete into smaller pieces for easier removal, as well as for outlining very clearly the area to be removed. The saws, however, are considered to be similar to the jackhammers now in the equipment list. Principal problems are that these breaking/sawing techniques are:

1. Slow
2. Add to congestion in the crater traffic patterns
3. Create a large amount of dust and fine debris which hinder other tasks
4. They require additional cleanup work by other machines.

The above listed disadvantages also generally apply to other commercially-available items such as rock-splitters and rock-drills.

EQUIPMENT WITH MINOR MODIFICATIONS

This modification category was directed by the RFP to include modifications costing less than 10 percent of the procurement price of the equipment. Because of the wide variety of sizes, attachments and configurations available as production items from U.S. manufacturers, this category would be more applicable to changes to existing BDR equipment.

Additionally, none of these modifications would preclude the BDR equipment from being used for other base construction functions.

Consequently, the following items were considered:

1. Ballasted vehicles
2. Sight holes in buckets and blades
3. Larger loader buckets.

Ballasting

Ballasting a vehicle, i.e., adding weight, can improve its performance up to a point. Increased traction and stability can be achieved, as long as the vehicle has a reserve of horsepower to haul the extra weight. Primary beneficiaries of added ballast are loaders, compactors and dozers that are to work on only slight grades and firm surfaces.

Rolling resistance of tires ranges from 40 pounds per ton of vehicle-plus-load weight on concrete to over 200 pounds per ton in loose fill areas. Therefore, in addition, the tire loading must be examined for an adequate tire size on a ballasted vehicle.

Ballasting of loaders is usually accomplished by adding weight on the rear frame, either with metal counterweights or with sand/rocks in a small load box. An alternate method is to add calcium chloride or a similar compound, often in a water solution, to the tires of the vehicle.

Compactors may be ballasted with either water or sand; many manufacturers provide load cavities for ballasting. Sheepsfoot rollers usually have a

water tank in the main drum; pneumatics have either a water tank or a sand box. Vibratory rollers may have a water tank with a capacity from 25 to 180 gallons.

Dozers are not usually ballasted, since they are usually designed to perform to their horsepower limit even on steep grades and soft soil.

Sight Holes

In films and reports on BDR techniques, the lack of visibility of dozer and loader operators required a ground director to guide them near the crater rim. The ground director, and resulting delays, can be alleviated by a simple modification: cutting sight holes along the upper edge of the blades and buckets. A row of 1 1/2-inch holes provides good visibility to the driver and causes only minor (at most) spillage, since the holes are near the top edge. These holes can be drilled or cut with a torch by military personnel in the maintenance shops. Some manufacturers offer these holes in optional equipment, with some models providing hooded slots to reduce spillage.

Larger Buckets

Larger bucket sizes are available for many loaders from the vehicle manufacturer. Given a specific make vehicle, the manufacturer's recommended size range can be obtained. A larger bucket within that range can often be substituted directly without changing linkages or hydraulics.

EQUIPMENT WITH MAJOR MODIFICATIONS

Major modifications to earthmoving equipment are seldom productive if the earthmoving task is a conventional construction-related technique. This results from the competitive market in construction equipment. If a significant need for a specialized equipment item develops, the equipment manufacturers become aware of the need and compete to market a satisfactory solution.

Consequently, even after extensive conversations with equipment producers and study of many special-equipment design programs in the military services, no large improvement was found by considering possible major modifications.

Only two possible equipment changes in this category finally resulted from the analysis; however, neither provided significant reductions in task times:

1. Logging Fork on Loader
2. Rock Rake on Dozer.

Logging Fork on Loader

One modification to equipment is addressed at reducing time in removing upheaved concrete. This concept is to mount a conventional logging fork attachment on a loader type vehicle. The forks are turned to point towards the vehicle and the linkages are extended. Such a vehicle could position the forks under the pavement lip and extract the pavement slab by reversing the vehicle and lifting the forks.

The advantages of such a modification were considered to be offset by the limitations in reach and the moment on the vehicle, a combination often faced now by shovels and Gradalls.

Rock Rake on Dozer

The other modification is the procurement of a standard item and creating a mounting scheme for it. A conventional rock rake, often used on crawler tractors in boulder-laden road work, would be adapted to a rubber-tired dozer and used to collect and move small-to-medium pieces of debris.

The attachment could be used for either spoiling or backfilling tasks. It provides good visibility to the operator and reduces the load loss incurred as the irregularly-shaped pieces drift off the edges of a conventional blade.

The advantage of the item is small, however, since large pieces of debris must still be moved singly, and small pieces can be graded off the runway.

NEW CONCEPTUAL EQUIPMENT

At a briefing during the performance of this study, two new equipment concepts were presented to USAF representatives, along with two new techniques. The Air Force did not approve the further development of any of these, hence no additional work was to be expended on them.

New Equipment Concepts

Briefly, the new equipment concepts were:

1. An attachment similar to a logging fork and employed as a pavement ripper mounted on a rubber-tired dozer.
2. A pavement ripper designed to be a work module for use with the U.S. Army FAMECE power module.

The logging fork-type pavement ripper was subsequently replaced in the BDR analysis by a crawler-mounted single-tooth ripper such as those currently in production by several manufacturers.

The FAMECE (FAMily of Engineering Construction Equipment) is an item currently being tested by the U.S. Army. It has a common power module which mates with a variety of work modules,e.g., a loader, a dump hauler, etc. It is not fully developed, as the prototype competition concluded in 1974 and service tests were to be performed in 1975.

NEW TECHNIQUES

The two new techniques for BDR both were specialized procedures directed toward pavement removal. One suggested technique was the use of explosives, either shaped charges or a plastic ribbon/liquid placed in saw-cut grooves. This was not considered a viable technique, since the BDR crews are not currently trained nor equipped for explosive work. In addition, the placement of such explosives might approach the minimum removal times of well-trained dozer excavator operators.

The second technique considered was the use of a Linde Lance for pavement cutting. This is a frame cutting tool which can cut concrete; however, the process is slow in thick concrete and requires special support equipment.

SECTION X

COST ANALYSIS

This report section presents the results of an analysis of cost-of-equipment versus BDR process times and task times. The times are those documented in Section VIII on a by-task, process-by-process, equipment mix-by equipment mix, crater type-by crater-type basis.

ANALYSIS APPROACH

The approach to cost analysis of an operation such as BDR, which is a "non-scheduled" activity on an individual-airbase level, has two elements:

1. Cost-accounting approach
2. Cost information sources and assumptions.

Cost Accounting Approach

The two alternate approaches to a cost-versus-performance tradeoff analysis are to either (1) use life-cycle costs, or (2) use first-costs only. Within each of these two approaches, additional decisions must be made as to which cost elements should (or can) be included in the accounting.

First-costs of equipment only was the selected cost parameter. This decision was,in effect, a by-default selection made because of a combination of two major reasons:

1. Equipment (and also, consumables and personnel) used in the BDR processes, on an individual airbase, are not used exclusively for BDR, nor is the cost of this equipment allocated for BDR purposes in terms of a specified percentage of its value, in the USAF accounting structure.
2. In order to use life-cycle-cost analysis, a specific lifetime usage scenario is required, but is not furnished by the USAF in AFR 93-2, other USAF recommended references, or in the additional references reviewed during this study.

Cost Information Assumptions and Sources

As regards to the makeup of the first costs, a sales price was used, FOB a common point (Los Angeles). The priced equipment is configured as described in Section VII and Appendix D. Generally, all safety and comfort options are included (roll-over protective structures, lights, operator stations comfort equipment, and all control options). Any portion that increases basic speed, reach, or load capacity over that noted in Appendix D is not included, nor are any ancilliary equipment such as winterizing kits, winches, etc.

Costs of minor modifications are not included because no time credit was claimed for the modifications.

Costs of transit to airbase, local taxes, and administrative costs connected with equipment acquisition are not included. Unit-price reductions for quantity purchases are not included.

All prices are 1976 prices obtained from direct contact with manufacturer

outlets in the Los Angeles area, or from at least two dealers if no manufacturer outlet existed in the area.

EQUIPMENT PRICES

The following is a list of equipment prices for not only the specific items used in Mix A, Mix B, and Mix C, but for the other items evaluated in Section VII and described in Appendix D. Prices are all subject to the qualifications of the previous paragraphs.

1.	Dozers (crawler type):		
	a. Caterpillar	D7F	$110,000
	b. Caterpillar	D8K	$159,000
	c. Terex	82-20	$ 81,000
	d. International Harvester	TD-20E	$103,000
2.	Dozers (rubber-tired): (with 2 1/2 or 3 1/2 cu. yd. bucket)		
	a. Caterpillar	814	$ 73,000
	b. Caterpillar	824	$134,000
	c. Caterpillar	834	$170,000
	d. Steiger	Bearcat	$140,000
	e. Steiger	Tiger	$160,000
3.	Loaders - Rubber Tired		
	a. Eaton	Yale 1700	$ 80,000
	b. Eaton	Yale 4000	$130,000
	c. Terex	72-71	$149,000
	d. Case	W26B	$ 70,000
	e. Clark	280	$124,000
	f. Clark	380	$187,000
	g. International Harvester	H500	$148,000
	h. Loader Fork Attachment	Yale	$ 1,000 (typical)
4.	Motor-Graders:		
	a. Caterpillar	12G	$ 70,000
	b. Galion	T-400	$ 46,000
	c. Wabco	440	$ 59,000
5.	Excavators:		
	a. Drott	80R	$130,000
	b. Bantam	S-155	$ 95,000
	c. Poclain	115P	$115,000
6.	Compactors:		
	a. Raygo	Rascal 400-A	$ 23,000
	b. Tampo	SP-950	$ 18,000
7.	Sweepers:		
	a. FMC Wayne	Dry/Vacuum	$ 32,000
	b. FMC Wayne	Wet/Vacuum	$ 50,000
	c. Tennant	Dry/Vacuum	$ 29,000
	d. AB Sweeping	(Brush)	$ 9,000

8. Single Tooth Hydraulic Operated Ripper:

a. ATECO			$ 9,000
b. Caterpillar			$11,000

9. Dump Trucks:

a.	International Loadstar	1700(5-ton)	$12,500
b.	International Fleetstar	F-2010A	$23,000

Other equipment items were also priced; only those prices are shown that relate to items that are in the USAF inventory and/or that had some feature or performance characteristics that resulted in its being analyzed as described in Section VII. (It is interesting to note that, based on unit sales prices obtained, that an equipment cost estimating parameter of two dollars per pound, dry and empty weight, would have been an accurate estimate for the listed equipment.)

Tables 42, 43, and 44 lists the particular prices associated with the three equipment mixes analyzed in Section VIII.

COST-TIME COMPARISONS

Tables 45 through 59 are a comparison of equipment cost versus time for the three equipment mixes, for each process, task, and crater type, for task times and for equipment mixes different between processes. Note that the equipment cost per task represents a total value of equipment allocated to a task; because some equipment, such as loaders, are used in more than one task, the costs should not be totaled on these charts. It is recommended that allocating a relative percent of an equipment item's cost to a task based on its relative percent of time involved not be used. This would be a misleading and/or distorted assumption relative to the "value" of a minute in one task versus its "value" in another task. Instead, the tables can be used to compare the cost of marginal decrease in task time in any one task, within a process type, due to an equipment addition or change. A comparison of the cost of marginal changes in process time from the aggregate changes in equipment is illustrated on Figure 23.

TABLE -42- EQUIPMENT MIX A PRICES (a)

ITEM	MODEL	UNIT PRICE	QTY	MIX PRICE
Crawler Dozer (a)	TD-20	$103,000	3	(a)$309,000
Loader	2 1/2 cu. yd. Bucket AC645 or Yale 1700	$ 80,000	7	$560,000
Loader Forks	Yale or Equiv.	$ 1,000	3	$ 3,000
5-Ton Truck	Loadstar 1700	$ 12,000	15	$187,500
Grader	Cat 12G	$ 70,000	3	$210,000
Compactor	VP4D	$ 18,000	3	$ 54,000
Tractor	75-Hp Ford (Equivalent)	$ 12,000	3	$ 36,000
Rotary Broom Sweeper	AB Sweeping	$ 9,000	2	$ 18,000
Vacuum Sweeper	Tennant	$ 24,000	2	$ 48,000
Jeep	Jeep	$ 8,000	2	$ 16,000
Excavator (a)	Poclain 115P	$115,000	3	(a)$345,000
		TOTAL:		$1,441,500
				(a)$1,477,500

(a) Crawler Dozer replaced by Excavator for UK Process, Small Crater BDR

TABLE -43- EQUIPMENT MIX B PRICES

ITEM	MODEL	UNIT PRICE	QTY	MIX PRICE
Crawler Dozer	TD-20	$103,000	3	$309,000
Loader	3 1/2 cu. yd. Bucket AC645	$ 80,000	7	$560,000
Loader Forks	Yale or Equiv.	$ 1,000	3	$ 3,000
10-Ton Truck	Fleetstar F-2010A	$ 23,000	15	$345,000
Grader	Cat 12G	$ 70,000	3	$210,000
Compactor	VP4D	$ 18,000	3	$ 54,000
Tractor	75-Hp Ford (Equivalent)	$ 12,000	3	$ 36,000
Rotary Broom Sweeper	Tennant	$ 9,000	2	$ 18,000
Vacuum Sweeper	Tennant	$ 29,000	2	$ 48,000
Jeep	Jeep	$ 8,000	2	$ 16,000
			TOTAL:	$1,599,000

TABLE -44- EQUIPMENT MIX C PRICES

ITEM	MODEL	UNIT PRICE	QTY	MIX PRICE
Crawler Dozer	TD-20	$103,000	3	$309,000
Ripper(on Crawler)	ATECO	$ 9,000	3	$ 27,000
Loader	Yale 1700 with 3 1/2 cu.yd. Bucket	$ 80,000	9	$560,000
Loader Forks	Yale or Equiv.	$ 1,000	3	$ 3,000
10-Ton Truck	Fleetstar F-2010A	$ 23,000	15	$345,000
Grader	Cat 12G	$ 70,000	3	$210,000
R-T Dozer	Steiger Bearcat	$140,000	3	$420,000
Excavator	Poclain 15-P	$115,000	3	$345,000
Compactor	Raygo Rascal 400A	$ 23,000	3	$ 69,000
Compactor	Tampo SP-950	$ 18,000	3	$ 54,000
Wet Brush Vacuum Sweeper	FMC Wayne "Airport"	$ 50,000	3	$150,000
			TOTAL:	$2,492,000

TABLE ~~45~~ VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

AFR 93-2 PROCESS, SINGLE LARGE CRATER,

EQUIPMENT MIX A. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	COST (b)
Backfill	17	1 Crawler Dozer 1R-T Loader	$183,000
Spoil	30	3 R-T Loaders	$240,000
Remove Lip	Included in Backfill	-	-
Remove Upheaval	30	1 Crawler 1 Dozer or 1 Loader with Fork	$103,000 or $ 80,000
Excavate	Not Applicable	-	-
Spoil Excavate	Not Applicable	-	-
Load	132	1/3 of R-T Loader	$ 27,000
Haul	135	5 5-Ton Trucks	$ 62,500
Grade (Cleanup)	35	3 Graders	$210,000
Grade (Level)	27	3 Graders	$210,000
Compact	60	1 Compactor	$ 18,000
Sweep	150	2/3 Rotary Broom Sweeper and Vacuum Sweeper	$ 26,000

(a) Refer to Tables 42-44 for Model Numbers and Total Process Costs
(b) Cost of equipment used on this task for 1 crater; does not sum costs from this Table
(c) Elapsed times for sequenced tasks are summed on Tables 23 thru 40
(d) Based on Table 23

TABLE -46- VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

AFR 93-2 PROCESS, SINGLE LARGE CRATER, EQUIPMENT MIX B. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	EQUIPMENT COST (b)
Backfill	17	1 Crawler 1 Loader	$183,000
Spoil	9	2 Loaders	$160,000
Remove Lip	Included in Backfill	-	-
Remove Upheaval	30	1 Loader 1 Loader/Forks	$161,000
Excavate	Not Applicable	-	-
Spoil Excavate	Not Applicable	-	-
Load	56	1/3 Loader	$ 27,000
Haul	60	5 10-Ton Trucks	$115,000
Grade (Cleanup)	25	3 Graders	$210,000
Grade (Level)	27	3 Graders	$210,000
Compact	30	1 Compactor	$ 18,000
Sweep	70	2/3 Rotary Sweeper 2/3 Vacuum Sweeper	$ 26,000

(a) Refer to Tables 42-44 for Model Numbers and Total Process Costs
(b) Cost of equipment used on this task for 1 crater; does not sum costs from this Table.
(c) Elapsed times for-sequenced tasks are summed on Tables 23 through 40
(d) Based on Table 24

TABLE -47- VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

AFR 93-2 PROCESS, SINGLE LARGE CRATER, EQUIPMENT MIX C. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	EQUIPMENT COST (b)
Backfill	17	1 Crawler 1 Loader	$183,000
Spoil	9	2 Loaders	$160,000
Remove Lip	Included in Backfill	-	-
Remove Upheaval	30	1 Crawler (with Ripper)	$112,000
Drift Stockpile	34	1 RT Dozer 1 Crawler Dozer	$183,000
Spoil Excavate	Not Applicable	-	-
Load	56	Loader	$ 80,000
Haul	60	5 10-Ton Trucks	$115,000
Grade (Cleanup)	25	3 Graders	$210,000
Grade (Level)	12	3 Graders	$210,000
Compact	15	1 Compactor	$ 54,000
Sweep	41	1 Wet Brush Sweeper 1 Vacuum Sweeper	$ 68,000

(a) Refer to Tables 42-44 for Model Numbers and Total Process Costs
(b) Cost of equipment used on this task for 1 crater; does not sum costs from this Table.
(c) Elapsed times for sequenced tasks are summed on Tables 23 through 40
(d) Based on Table 25

TABLE -48- VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

U.K. PROCESS, SINGLE LARGE CRATER, EQUIPMENT MIX A. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	COST (b)
Backfill	Not Applicable	-	-
Spoil	17	1 Loader	$180,000
Drift Stockpile	106	1 Crawler	$103,000
Remove Lip	28	1 Crawler	$103,000
Remove Upheaval	30	1 Loader with Forks	$ 81,000
Excavate	31	1 Crawler	$103,000
Spoil Excavate	181	2 Loaders	$160,000
Load	276	1/3 Loader	$ 27,000
Haul	280	5 Trucks	$ 62,500
Grade (Cleanup)	27	3 Graders	$210,000
Grade (Level)	12	2 Graders	$140,000
Compact	100	1 Compactor	$ 18,000
Sweep	313	2/3 Rotary Broom 2/3 Vacuum Sweeper	$ 26,000

(a) Refer to Tables 42-44 for Model Numbers and Total Process Costs

(b) Cost of equipment used on this task for 1 crater, does not sum costs form this Table.

(c) Elapsed times for sequenced tasks are summed on Tables 23 through 40

(d) Based on Table 26

TABLE -49- VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

U.K. PROCESS, SINGLE LARGE CRATER, EQUIPMENT MIX B. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	EQUIPMENT COST (b)
Backfill	Not Applicable	-	-
Spoil	106	1 Loader	$ 80,000
Drift Stockpile	17	1 Crawler	$103,000
Remove Lip	28	1 Crawler	$103,000
Remove Upheaval	30	1 Loader with Forks	$ 81,000
Excavate	31	1 Crawler	$103,000
Spoil Excavate	181	2 Loaders	$160,000
Load	110	1/3 Loader	$ 27,000
Haul	115	5 Trucks	$115,000
Grade (Cleanup)	27	3 Graders	$210,000
Grade (Level)	12	2 Graders	$140,000
Compact	30	1 Compactor	$ 18,000
Sweep	20	2/3 Rotary Broom 2/3 Vacuum Sweeper	$ 26,000

(a) Refer to Tables 42-44 for Model Numbers and Total Process Costs
(b) Cost of equipment used on this task for 1 crater; does not sum costs from this Table.
(c) Elapsed times for sequenced tasks are summed on Tables 23 through 40
(d) Based on Table 27

TABLE -50- VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

U.K. PROCESS, SINGLE LARGE CRATER, EQUIPMENT MIX C. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	COST (b)
Backfill	Not Applicable	-	-
Drift Stockpile	106	1 Crawler	$103,000
Spoil	106	1 Loader	$ 80,000
Remove Lip	28	R-T Dozer	$140,000
Remove Upheaval	30	1 Crawler	$103,000
Excavate	33	1 Excavator	$115,000
Spoil Excavate	145	1 Loader 1 R-T Dozer	$220,000
Load	94	1 Loader	$ 80,000
Haul	98	5 Trucks	$115,000
Grade (Cleanup)	52	3 Graders	$210,000
Grade (Level)	12	1 Grader	$140,000
Compact	60	1 Compactor	$ 18,000
Sweep	20	1 Rotary Brush Sweeper	$ 26,000

(a) Refer to Tables 42-44 for Model Numbers and Total Process Costs
(b) Cost of equipment used on this task for 1 crater; does not sum costs from this Table
(c) Elapsed times for sequenced tasks are summed on Tables 23 through 40
(d) Based on Table 28

TABLE -51- VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

ADVANCED FILL PROCESS, SINGLE LARGE CRATER, EQUIPMENT MIX A or B. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	COST (b)
Backfill	Not Applicable		
Spoil	38	2 Loaders	$160,000
Remove Lip	28	1 Crawler	$103,000
Remove Upheaval	38	1 Loader with Forks	$ 81,000
Excavate	Not Applicable	-	-
Spoil Excavate	Not Applicable	-	-
Load	Not Applicable	-	-
Haul	Not Applicable	-	-
Grade (Cleanup) (Runway)	52	1/3 Grader	$ 23,000
Grade (Level)	Not Applicable	-	-
Compact	Not Applicable	-	-
Sweep	79	1 Rotary Sweeper 1 Vacuum Sweeper	$ 66,000

(a) Refer to Tables 42-44 for Model Numbers and Total Process Costs
(b) Cost of equipment used on this task for 1 crater; does not sum costs from this Table
(c) Elapsed times for sequenced tasks are summed on Tables 23 through 40
(d) Based on Table 29

TABLE -52- VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

ADVANCED FILL PROCESS, SINGLE LARGE CRATER, EQUIPMENT MIX C. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	EQUIPMENT COST (b)
Backfill	Not Applicable	-	-
Spoil	17	1 Loader	$ 80,000
Spoil Upheaval	13	1 R-T Dozer	$220,000
Remove Lip	14	1 Loader 1 Crawler 1 R-T Dozer	$220,000
Remove Upheaval	22	1 Loader with Forks 1 Crawler	$184,000
Excavate	Not Applicable	-	-
Spoil Excavate	Not Applicable	-	-
Load	Not Applicable	-	-
Haul	Not Applicable	-	-
Grade (Cleanup) (Runway)	40	1/3 Grader	$ 23,000
Grade (Level)	Not Applicable	-	-
Compact	Not Applicable	-	-
Sweep	30	Wet Brush Vacuum Sweeper	$ 50,000

(a) Refer to Tables 42-44 for Model Numbers and Total Process Costs
(b) Cost of equipment used on this task for 1 crater; does not sum costs fr from this Table
(c) Elapsed times for sequenced tasks are summed on Tables 23 through 40
(d) Based on Table 30

TABLE -53- VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

AFR 93-2 PROCESS, SINGLE SMALL OPEN CRATER EQUIPMENT MIX A or B. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	COST (b)
Backfill	4	1 Crawler	$103,000
Spoil	7	1 Loader	$ 80,000
Spoil Upheaval	9	1 Crawler 1 Loader	$183,000
Remove Lip	4	1 Crawler	$103,000
Remove Upheaval	6	1 Loader with Forks	$ 81,000
Excavate	Not Applicable	-	-
Spoil Excavate	Not Applicable	-	-
Load	16	1/3 Loader	$ 27,000
Haul	20	5 Trucks	$ 62,500
Grade (Cleanup)	25	3 Graders	$210,000
Grade (Level)	6	1 Grader	$ 70,000
Compact	22	1 Compactor	$ 18,000
Sweep	18	2/3 Rotary Brush 2/3 Vacuum Sweeper	$ 26,000

(a) Refer to Tables **42-44** for Model Numbers and Total Process Costs
(b) Cost of equipment used on this task for 1 crater; does not sum costs from this Table
(c) Elapsed times for sequenced tasks are summed on Tables 23 through 40
(d) Based on Table 31

TABLE -54- VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

AFR 93-2 PROCESS, SINGLE SMALL OPEN CRATER, EQUIPMENT MIX C. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	EQUIPMENT COST (b)
Backfill	4	1 Crawler	$103,000
Spoil	10	2 Loaders 1 Crawler	$263,000
Remove Lip	4	1 Crawler	$103,000
Remove Upheaval	5	1 Excavator	$115,000
Excavate	Not Applicable	-	-
Spoil Excavate	Not Applicable	-	-
Load	8	1 Loader	$ 8,000
Haul	12	5 Trucks	$115,000
Grade (Cleanup)	34	3 Graders	$210,000
Grade (Level)	6	1 Grader	$ 70,000
Compact	22	1 Compactor	$ 18,000
Sweep	7	1 Wet Brush Sweeper	$ 48,000

(a) Refer to Tables 42-44 for Model Numbers and Total Process Costs
(b) Cost of equipment used on this task for 1 crater; does not sum costs from this Table
(c) Elapsed times for sequenced tasks are summed on Tables 23 through 40
(d) Based on Table 32

TABLE -55- VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

AFR 93-2 PROCESS, SINGLE SMALL CAMOUFLET CRATER, EQUIPMENT MIX A or B. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	EQUIPMENT COST (b)
Backfill	4	1 Crawler	$103,000
Spoil	7	1 Loader	$ 80,000
Spoil Upheaval	25	1 Loader 1 Crawler	$183,000
Open Vent	15	1 Loader with Forks	$ 81,000
Remove Upheaval	15	1 Loader with Forks	$ 81,000
Excavate	Not Applicable	-	-
Spoil Excavate	Not Applicable	-	-
Load	8	1/3 Loader	$ 27,000
Haul	37	5 Trucks	$ 62,500
Grade (Cleanup)	25	3 Graders	$210,000
Grade (Level)	6	1 Grader	$ 70,000
Compact	12	1 Compactor	$ 18,000
Sweep	7	2/3 Rotary Brush 2/3 Vacuum Sweeper	$ 26,000

(a) Refer to Tables 42-44 for Model Numbers and Total Process Costs
(b) Cost of equipment used on this task for 1 crater; does not sum costs from this Table
(c) Elapsed times for sequenced tasks are summed on Tables 23 through 40
(d) Based on Table 33

TABLE -56- VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

AFR 93-2 PROCESS, SINGLE CAMOUFLET CRATER, EQUIPMENT MIX C. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	EQUIPMENT COST (b)
Backfill	4	1 Crawler	$103,000
Spoil	15	2 Loaders	$160,000
Open Vent	8	1 Excavator	$115,000
Remove Upheaval	5	1 Excavator	$115,000
Excavate	Not Applicable	-	-
Spoil Excavate	Not Applicable	-	-
Load	8	1 Loader	$ 80,000
Haul	24	5 Trucks	$115,000
Grade (Cleanup)	25	3 Graders	$210,000
Grade (Level)	6	1 Grader	$ 70,000
Compact	12	1 Compactor	$ 18,000
Sweep	7	1 Wet Brush Sweeper	$ 48,000

(a) Refer to Tables **42-44** for Model Numbers and Total Process Costs
(b) Cost of equipment used on this task for 1 crater; does not sum costs from this Table.
(c) Elapsed times for sequenced tasks are summed on Tables 23 through 40
(d) Based on Table 34

TABLE -57- VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

U.K. PROCESS, SMALL OPEN CRATER, EQUIPMENT MIX A. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	EQUIPMENT COST (b)
Backfill	Not Applicable	-	-
Spoil	23	2 Loaders	$160,000
Remove Lip	1	1 Excavator	$115,000
Remove Upheaval	13	1 Excavator	$115,000
Excavate	7	1 Excavator	$115,000
Spoil Excavate	10	1 Loader	$ 80,000
Load	24	1/3 Loader	$ 27,000
Haul	46	5- Trucks	$115,000
Grade (Cleanup)	25	3 Graders	$210,000
Grade (Level)	6	1 Grader	$ 70,000
Compact	22	1 Compactor	$ 18,000
Sweep	7	2/3 Rotary Brush 2/3 Vacuum Sweeper	$ 26,000

(a) Refer to Tables 42-44 for Model Numbers and Total Process Costs
(b) Coat of equipment used on this task for 1 crater; does not sum costs from the Table
(c) Elapsed times for sequenced tasks are summed on Tables 23 through 40
(d) Based on Table 35

TABLE -58- VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

U.K. PROCESS, SINGLE SMALL OPEN LARGE CRATER, EQUIPMENT MIX B. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	EQUIPMENT COST (b)
Backfill	Not Applicable	-	-
Spoil	23	2 Loaders	$ 80,000
Remove Lip	7	1 Excavator	$115,000
Remove Upheaval	13	1 Excavator	$115,000
Excavate	7	1 Excavator	$115,000
Spoil Excavate	10	1 Loader	$ 80,000
Load	12	1/3 Loader	$ 27,000
Haul	16	5 Trucks	$115,000
Grade (Cleanup)	31	3 Graders	$210,000
Grade (Level)	12	1 Grader	$ 70,000
Compact	22	1 Compactor	$ 18,000
Sweep	7	2/3 Rotary Brush 2/3 Vacuum Sweeper	$ 26,000

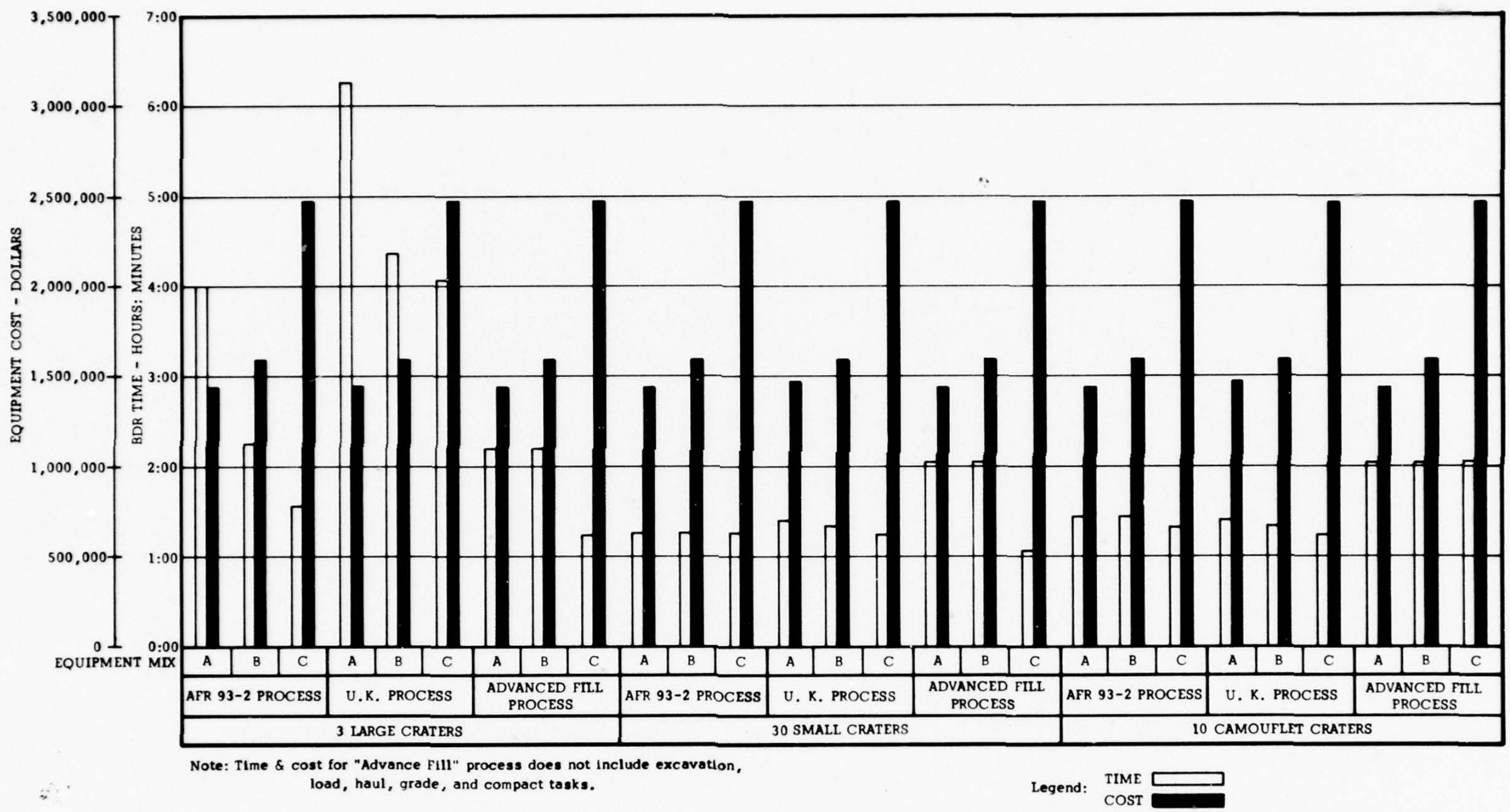
(a) Refer to Tables 42-44 for Model Numbers and Total Process Costs
(b) Cost of equipment used on this task for 1 crater; does not sum costs from this Table
(c) Elapsed times for sequenced tasks are summed on Tables 23 through 40
(d) Based on Table 36

TABLE -59- VALUE OF EQUIPMENT ALLOCATED TO INDIVIDUAL BDR TASKS;

U.K. PROCESS, SMALL OPEN CRATER, EQUIPMENT MIX C. (a) (d)

SUBTASK	LONGEST ELAPSED TIME-MINUTES (c)	EQUIPMENT TYPE/QTY	EQUIPMENT COST (b)
Backfill	Not Applicable	-	-
Spoil	23	2 Loaders	$ 80,000
Remove Lip	7	1 Excavator	$115,000
Remove Upheaval	13	1 Excavator	$115,000
Excavate	7	1 Excavator	$115,000
Spoil Excavate	10	1 Crawler	$103,000
Load	4	1 Loader	$ 80,000
Haul	16	5 Trucks	$115,000
Grade (Cleanup)	31	3 Graders	$210,000
Grade (Level)	6	1 Grader	$ 70,000
Compact	11	2 Compactors	$ 36,000
Sweep	7	1 Wet Brush Sweeper	$ 50,000

(a) Refer to Tables 42-44 for Model Numbers and Total Process Costs
(b) Cost of equipment used on this task for 1 crater; does not sum costs from this Table
(c) Elapsed times for sequenced tasks are summed on Tables 23 through 40
(d) Based on Table 37



Note: Time & cost for "Advance Fill" process does not include excavation, load, haul, grade, and compact tasks.

Figure 23 . Summary of BDR Times and Equipment Costs

Interpretation of Analysis

Several factors should be considered in basing any decisions on the cost-versus-time analysis presented on the preceeding charts:

1. The true cost-of-ownership of the equipment mixes analyzed for BDR will include not only the BDR-proportionate shape of acquisitions costs, but also the consumables and maintenance allocated specifically to BDR excercises and operations. However, if these added cost elements are estimated to be some specific percentage of the original price (ie: 20% per year, for example), the effect on the marginal cost change for a marginal change in repair time can be readily accomplished. Even though the life-cycle cost approach was not a study requirement, a brief analysis shows that the relative ranking of equipment mixes in terms of time maintains the same ranking in terms of cost even with other ownership costs added.
2. Within some tasks, different equipment types are used, and equipment used in tasks is sequenced differently, between processes; therefore, between - process task comparisons are not considered to be useful based on either cost, cost versus time, or time only. The within-a process equipment-mix comparisons are the most useful, because the time and cost estimates are made with a common statement of work, and directly illustrate the marginal gain/marginal cost tradeoff.
3. Addition or deletion of options on a piece of equipment on an individual basis should not be done in any further case analysis; the equipment priced have equivalent features.
4. There is absolutely no implication of a parametric relationship between cost and time in the cost-time analysis; as discussed in Section VII and VIII, the minimum possible times indicated in the analysis cannot be bettered by using more money to add more equipment, due to the physical limits of the repair problem, with existing and/or modified equipment.

At best only the marginal time improvements shown, and/or more reliably - achieved planning - purpose times, can be expected by adding or modifying BDR equipment mixes.

SECTION XI

CONCLUSIONS

1. Trucks should be upgraded from 5-ton to 10-ton capacity, since large craters repairs are timed-limited by hauling times.
2. Increased and different types of compaction equipment are necessary.
3. Additional dozers will reduce repair times.
4. An excavator should be added for the small crater threat; it is useful on large craters as well. A large dozer with ripper is an alternate to the excavator.
5. The number of graders is adequate there should be three loaders in the stockplie, one per each 5 trucks; the loader bucket size should be increased to 3 1/2 cubic yards to match the trucks.
6. The towed broom sweepers should be replaced by self-propelled, wet spray types.
7. BDR times are primarily limited by the small area each crater occupies. Only three or four vehicles can work the area simultaneously. Small craters are even more restrictive.
8. Radio contact is necessary for coordinating activities between crater and base stockpile and between crews. The OIC must be experienced in earth fill techniques and vehicle usage.
9. Maximum use should be made of flags and pylons (flashers at night) to indicate turn points on haul roads and to designate dedicated areas such as mat assembly and temporary stockpiles.
10. Minor equipment modifications can produce worthwhile increases in efficiency and, hence, increase the probability of regularly achieving planned repair times in a large range of working conditions reduced repair times.
11. Major modifications or new equipment concepts are [illegible] practical because costs would not be justified relative to the time gained.

APPENDIX A

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CONCEPTS, PROCESSES AND EQUIPMENT

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APPENDIX B

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APPENDIX C. COMPUTER PROGRAMS

The computer programs used in this study were written in Extended Basic language and run on a time-share system at a remote terminal.

Table C-1 defines the dozer program input variables. All programs run in a foot - pound - minute system, with angles in radians. Although the program is titled Dozer Spoiling, it has been revised to accommodate backfill analysis as well.

Table C-2 lists program variables calculated by the computer during the analysis of input data. Subsequent pages provide a program listing for Dozer Spoiling, with sample runs following the listing.

Table C-3 presents a Truck Hauling listing, with a comparison of 5-ton and 10-ton truck teams both supported by a 3.5 cubic yard loader.

TABLE C-1 DOZER PROGRAM INPUT VARIABLES

N	Number of driven vehicle elements, i.e. wheels or tracks
G	Ground contact area (square feet per driven element)
C	Coefficient of soil cohesion (pounds per square foot)
W	Vehicle working weight, (pounds)
P1	Angle of soil shear, Ø, (radians)
D	Haul distance, (feet)
R	Rolling resistance of driven elements (pound per pound)
G1	Working grade (radians)
RØ	Material density, (pounds per cubic foot)
M	Coefficient of sliding friction ,μ(dimensionless)
H	Horsepower of vehicle
M1	Mechanical efficiency of vehicle power train
T2	Task limited velocity, (feet per minute)
T3	Task limited velocity, returning, (feet per minute)
I1	Cycle fixed time, loading , (minutes)
I2	Cycle fixed time, unloading, (minutes)
E	Job efficiency

TABLE C-2 DOZER SPOILING DEBRIS PROGRAM VARIABLES

T1	Maximum available tractive effort, (pounds)
F1	Drag forces due to vehicle weight, tire pressure and working grade (pounds)
F2	Drag force due to vehicle haul load, (pounds)
V1	Maximum vehicle velocity, horsepower limited, (feet per minute)
L1	Maximum vehicle velocity, load limited, (feet per minute)
T9	Sum of vehicle work cycle times, (minutes)
TØ	Time to complete total work-adjusted for work efficiency, (hours)

TABLE C - 3 TRUCK TEAMS HAULING FILL INPUT VARIABLES

V	Haul volume of truck, (cubic feet)
H	Horsepower of truck
W	Empty weight, (pounds)
N	Number of driven wheels
D	Haul and return distance, (feet)
W3	Ton rating of truck, (pounds)
B1	Bucket cycle time, (minutes)
B	Bucket volume, (cubic feet)
T4	Spotting time, (minutes)
T5	Dump time, (minutes)
G	Ground contact area, (square feet)
C	Soil cohesion
P1	Soil shear angle, (radians)
R	Rolling resistance, (pounds per pound)
GL	Working grade, (radians)
RØ	Material density, (pounds per cubic foot)
M1	Mechanical efficiency
V2	Maximum haul velocity, (feet per minute)
V4	Maximum return velocity, (feet per minute)
E	Job efficiency

TABLE C-3 (Continued)

Q1	Queue time at loader, (minutes)
Q2	Queue time at work area, (minutes)
N1	Number of trucks on task
W1	Total fill volume for job, (cubic feet)

```
 LIST 1,9999
0005 DIM A$[10],B$[10],C$[10]
0015 REM THIS PROGRAM IS FOR CALCULATING THE PRODUCTIVITY OF A
0025 REM DOZER SPOILING DEBRIS.
0035 REM THE INPUT VARIABLES ARE DEFINED AS FOLLOWS:
0045 REM N IS NUMBER OF DRIVEN VEHICLE ELEMENTS,G IS THE GROUND
0055 REM  CONTACT AREA OF A SINGLE WHEEL,C COEFFICIENT OF SOIL
0065 REM COHESION,W VEHICLE WORKING WEIGHT,P1 ANGLE OF SOIL SHEAR,
0075 REM D AVERAGE HAUL DISTANCE,R VEHICLE ROLLING RESISTANCE
0085 REM G1 WORKING GRADE,R0 MATERIAL DENSITY,V HAUL VOLUME,
0095 REM M COEFFICIENT OF SLIDING FRICTION,H HORSEPOWER RATING ,
0105 REM M1 VEHICLE/TOOL MECHANICAL EFFICIENCY, T2 AND T3 MAXIMUM
0115 REM VELOCITY ON A TASK, I1 AND I2  FIXED TIMES IN A CYCLE,
0125 REM AND E OPERATOR EFFICIENCY
0135 PRINT "IS THIS DOZER SPOIL OR BACKFILL";
0145 INPUT A$
0155 IF A$="BACKFILL"THEN GOTO 0215
0165 PRINT "IS THIS FOR A LARGE OR A SMALL CRATER";
0175 INPUT B$
0185 IF B$="SMALL"THEN LET K=2
0195 IF B$="LARGE"THEN LET K=1
0205 GOTO 0247
0215 PRINT "IS THIS FOR LARGE OR SMALL CRATERS";
0225 INPUT B$
0235 IF B$="LARGE"THEN LET K=3
0245 IF B$="SMALL"THEN LET K=4
0247 PRINT "HOW MANY VEHICLES TO BE PROCESSED";
0248 INPUT N9
0255 PRINT "THIS ANALYSIS IS FOR "A$" IN THE EVENT OF "B$" CRATERS"
0260 PRINT
0261 PRINT "THE DISTANCE IS ";
0262 PRINT "60";
0263 PRINT " FEET THEREFORE THE VEHICLES WILL HANDLE"
0264 PRINT "THE ENTIRE POPULATION"
0265 PRINT
0266 PRINT
0285 PRINT "VEH. NO.","PROD.","TOTAL TIME","DISTANCE"
0295 FOR J=1TO N9
0305   READ N,G,C,W,P1,D
0310   LET D=60
0315   LET T1=N*G*C+W*TAN(P1)
0325   READ R,G1
0335   LET F1=T1-(W*R)-(W*SIN(G1))
0345   READ R0,D1,M
0355   LET R9=R0*M+R0*R+R0*SIN(G1)
0365   ON KTHEN GOSUB 1635, 2115, 2165, 2115
0375   READ H,M1
0385   LET V1=33000*H*M1/T1
0395   READ T2
0405   IF V1<T2THEN GOTO 0425
0415   LET V1=T2
0425   ON KTHEN GOSUB 0765, 1195, 2615, 1195
0435   READ T3,I1,I2
```

```
0445   LET Z=D/T3
0455   READ E
0465   LET T9=W2*(Z+I1+I2)+X
0475   LET P=V2*60*E/T9
0485   LET T0=T9*E/60
0495   PRINT J,P,T0,D
0505 NEXT J
0515 END
0530 REM CASE W26B
0532 DATA 4,2.59,1,33045,.62,65,.02,.01,140,1,.5
0534 DATA 165,.75,1800,2631,.1,.1,.7
0540 REM CAT 814
0542 DATA 4,2.59,1,36000,.62,65,.02,.01,140,1,.5,170
0544 DATA .75,1742,1742,.1,.1,.7
0550 REM CAT 824
0552 DATA 4,4.41,1,62400,.62,65,.02,.01,140,1,.5
0554 DATA 300,.75,1628,1628,.1,.1,.7
0560 REM CAT 834
0562 DATA 4,4.8,1,76000,.62,65,.02,.01,140,1,.5
0564 DATA 400,.75,1795,1795,.1,.1,.7
0570 REM CAT D7F
0572 DATA 2,14.86,.5,44600,.46,65,0,.01,140,1,.5
0574 DATA 180,.75,519,519,.1,.1,.7
0580 REM CAT D8K
0582 DATA 2,17.57,.5,69950,.46,65,0,.01,140,1,.5
0584 DATA 300,.75,590,590,.1,.1,.7
0590 REM CLARK 280
0592 DATA 4,4.41,1,69700,.62,65,.02,.01,140,1,.5
0594 DATA 301,.75,1800,2534,.1,.1,.7
0600 REM CLARK 380
0602 DATA 4,5.71,1,116000,.62,65,.02,.01,140,1,.5
0604 DATA 472,.75,1786,1786,.1,.1,.7
0610 REM YALE 1700
0612 DATA 4,1.31,1,18045,.62,65,.02,.01,140,1,.5
0614 DATA 104,.75,1601,1601,.1,.1,.7
0620 REM YALE 4000
0622 DATA 4,3.13,1,46500,.62,65,.02,.01,140,1,.5
0624 DATA 260,.75,1800,1865,.1,.1,.7
0630 REM IH 560
0632 DATA 4,4.41,1,76250,.62,65,.02,.01,140,1,.5
0634 DATA 380,.75,1800,1953,.1,.1,.7
0640 REM IH TD-20
0642 DATA 2,16.57,.5,39950,.46,65,0,.01,140,1,.5
0644 DATA 210,.75,561,561,.1,.1,.7
0650 REM BEARCAT
0652 DATA 4,5.1,1,23000,.62,65,.02,.01,140,1,.5
0654 DATA 210,.75,1800,1839,.1,.1,.7
0660 REM TIGER
0662 DATA 4,5.1,1,32000,.62,65,.02,.01,140,1,.5
0664 DATA 272,.75,1551,1551,.1,.1,.7
0670 REM TEREX 72-71
0672 DATA 4,4.41,1,76250,.62,65,.02,.01,140,1,.5
0674 DATA 336,.75,1800,1830,.1,.1,.7
```

```
0680 REM TEREX 82-20
0682 DATA 2,14.86,.5,36885,.46,65,0,.01,140,1,.5
0684 DATA 180,.75,616,616,.1,.1,.7

0765 LET X=0
0775 IF B=1THEN GOTO 0845
0785 IF B=2THEN GOTO 0905
0795 IF B=3THEN GOTO 0965
0805 IF B=4THEN GOTO 1025
0815 REM B=5
0825 GOTO 1085
0835 PRINT "THERE IS AN ERROR SOMEWHERE"
0845 LET L1=33000*H*M1/F3
0855 IF L1=<T2THEN GOTO 0875
0865 LET L1=T2
0875 LET X=1*D/L1
0885 LET F2=121*D1*R9
0895 LET F3=F1-F2
0905 LET L1=33000*H*M1/F3
0915 IF L1=<T2THEN GOTO 0935
0925 LET L1=T2
0935 LET X=X+3*D/L1
0945 LET F2=81*D1*R9
0955 LET F3=F1-F2
0965 LET L1=33000*H*M1/F3
0975 IF L1=<T2THEN GOTO 0995
0985 LET L1=T2
0995 LET X=X+9*D/L1
1005 LET F2=49*D1*R9
1015 LET F3=F1-F2
1025 LET L1=33000*H*M1/F3
1035 IF L1=<T2THEN GOTO 1055
1045 LET L1=T2
1055 LET X=X+17*D/L1
1065 LET F2=25*D1*R9
1075 LET F3=F1-F2
1085 LET L1=33000*H*M1/F3
1095 IF L1=<T2THEN GOTO 1115
1105 LET L1=T2
1115 LET X=X+29*D/L1
1125 LET F2=9*D1*R9
1135 LET F3=F1-F2
1145 LET L1=33000*H*M1/F3
1155 IF L1=<T2THEN GOTO 1175
1165 LET L1=T2
1175 LET X=X+44*D/L1
1185 RETURN
```

```
1195 REM ASSUME ENTIRE POPULATION AT T2 (MAX SPEED)
1205 LET F2=49*D1*R9
1215 LET F3=F1-F2
1225 LET L1=33000*H*M1/F3
1235 IF L1=<T2THEN GOTO 1255
1245 LET L1=T2
1255 LET X=D/L1
1265 LET F2=36*D1*R9
1275 LET F3=F1-F2
1285 LET L1=33000*H*M1/F3
1295 IF L1=<T2THEN GOTO 1315
1305 LET L1=T2
1315 LET X=X+2*D/L1
1325 LET F2=25*D1*R9
1335 LET F3=F1-F2
1345 LET L1=33000*H*M1/F3
1355 IF L1=<T2THEN GOTO 1375
1365 LET L1=T2
1375 LET X=X+3*D/L1
1385 LET F2=16*D1*R9
1395 LET F3=F1-F2
1405 LET L1=33000*H*M1/F3
1415 IF L1=<T2THEN GOTO 1435
1425 LET L1=T2
1435 LET X=X+4*D/L1
1445 LET F2=9*D1*R9
1455 LET F3=F1-F2
1465 LET L1=33000*H*M1/F3
1475 IF L1=<T2THEN GOTO 1495
1485 LET L1=T2
1495 LET X=X+6*D/L1
1505 LET F2=4*D1*R9
1515 LET F3=F1-F2
1525 LET L1=33000*H*M1/F3
1535 IF L1=<T2THEN GOTO 1555
1545 LET L1=T2
1555 LET X=X+10*D/L1
1565 LET F2=1*D1*R9
1575 LET F3=F1-F2
1585 LET L1=33000*H*M1/F3
1595 IF L1=<T2THEN GOTO 1615
1605 LET L1=T2
1615 LET X=X+21*D/L1
1625 RETURN
```

```
1635 FOR B=1TO 5
1645   IF B=1THEN GOSUB 2045
1655   IF B=1THEN LET V=169*D1
1665   IF B=2THEN LET V=121*D1
1675   IF B=3THEN LET V=81*D1
1685   IF B=4THEN LET V=49*D1
1695   IF B=5THEN LET V=25*D1
1705   LET F2=V*R9
1715   LET F3=F1-F2
1725   IF F3=>0THEN GOTO 1765
1735 NEXT B
1745 PRINT "VEHICLE CANNOT EVEN HANDLE MEAN-1 SIGMA CHUNK SIZE"
1755 GOTO 0505
1765 IF B=1THEN GOTO 1855
1775 IF B=2THEN GOTO 1895
1785 IF B=3THEN GOTO 1945
1795 IF B=4THEN GOTO 1995
1805 REM ;J" CAN HANDLE THE MEAN-1 SIGMA"
1815 LET W1=29*25+44*9
1825 LET W2=29+44
1835 LET V2=W1*D1
1845 RETURN
1855 LET W1=1*169+3*121+9*81+17*49+29*25+44*9
1865 LET W2=1+3+9+17+29+44
1875 LET V2=D1*W1
1885 RETURN
1895 REM;J" CAN HANDLE MEAN+2 SIGMA"
1905 LET W1=3*121+9*81+17*49+29*25+44*9
1915 LET W2=3+9+17+29+44
1925 LET V2=D1*W1
1935 RETURN
1945 REM;J" CAN HANDLE THE MEAN+1 SIGMA"
1955 LET W1=9*81+17*49+29*25+44*9
1965 LET W2=9+17+29+44
1975 LET V2=D1*W1
1985 RETURN
1995 REM;J"WILL HANDLE THE MEAN CHUNK SIZE"
2005 LET W1=17*49+29*25+44*9
2015 LET W2=17+29+44
2025 LET V2=D1*W1
2035 RETURN
2045 IF D=60THEN LET B=1
2055 IF D=55THEN LET B=2
2065 IF D=50THEN LET B=3
2075 IF D=35THEN LET B=4
2085 IF D=20THEN LET B=5
2095 REM IFD<>60 ;"D="D" THEREFORE ";
2105 RETURN
2115 REM ASSUME MACHINERY CAN HANDLE THE ENTIRE POPULATION
2125 LET W1=1*49+2*36+3*25+4*16+6*9+10*4+21*1
2135 LET W2=1+2+3+4+6+10+21
2145 LET V2=W1*D1
2155 RETURN
```

```
2165 FOR B1=1TO 5
2175   IF B1=1THEN GOSUB 2295
2185   IF B1=1THEN LET V=169*D1
2195   IF B1=2THEN LET V=121*D1
2205   IF B1=3THEN LET V=81*D1
2215   IF B1=4THEN LET V=49*D1
2225   IF B1=5THEN LET V=25*D1
2235   LET F2=V*R9
2245   LET F3=F1-F2
2255   IF F3=>0THEN GOTO 2365
2265 NEXT B1
2275 PRINT "VEHICLE'S LOAD IS INDETERMINABLE"
2285 GOTO 0505
2295 IF D=65THEN LET B1=1
2305 IF D=45THEN LET B1=2
2315 IF D=30THEN LET B1=3
2325 IF D=15THEN LET B1=4
2335 IF D=10THEN LET B1=5
2340 IF D=5THEN LET B1=5
2345 REM IF D<> 65 ;"D="D" THEREFORE"
2355 RETURN
2365 ON B1THEN GOTO 2425, 2465, 2515, 2565, 2375
2375 REM;J" WILL HANDLE MEAN+2 AND LARGER "
2385 LET W1=1*169+121*3
2395 LET W2=1+3
2405 LET V2=D1*W1
2415 RETURN
2425 LET W1=1*169+3*121+9*81+17*49+29*25+44*9
2435 LET W2=1+3+9+17+29+44
2445 LET V2=W1*D1
2455 RETURN
2465 REM;J" WILL HANDLE MEAN-1 SIGMA AND LARGER"
2475 LET W1=1*169+3*121+9*81+17*49+29*25
2485 LET W2=1+3+9+17+29
2495 LET V2=W1*D1
2505 RETURN
2515 REM ;J" WILL HANDLE THE MEAN AND LARGER"
2525 LET W1=1*169+3*121+9*81+17*49
2535 LET W2=1+3+9+17
2545 LET V2=W1*D1
2555 RETURN
2565 REM;J" WILL HANDLE MEAN + 1 SIGMA AND LARGER"
2575 LET W1=1*169+3*121+9*81
2585 LET W2=1+3+9
2595 LET V2=W1*D1
2605 RETURN
```

```
2615 LET X=0
2625 ON B1THEN GOTO 2635, 2695, 2755, 2815, 2875
2635 LET F2=9*D1*R9
2645 LET F3=F1-F2
2655 LET L1=33000*H*M1/F3
2665 IF L1=<T2THEN GOTO 2685
2675 LET L1=T2
2685 LET X=44*D/L1
2695 LET F2=25*D1*R9
2705 LET F3=F1-F2
2715 LET L1=33000*H*M1/F3
2725 IF L1=<T2THEN GOTO 2745
2735 LET L1=T2
2745 LET X=X+29*D/L1
2755 LET F2=49*D1*R9
2765 LET F3=F1-F2
2775 LET L1=33000*H*M1/F3
2785 IF L1=<T2THEN GOTO 2805
2795 LET L1=T2
2805 LET X=X+17*D/L1
2815 LET F2=81*D1*R9
2825 LET F3=F1-F2
2835 LET L1=33000*H*M1/F3
2845 IF L1=<T2THEN GOTO 2865
2855 LET L1=T2
2865 LET X=X+9*D/L1
2875 LET F2=121*D1*R9
2885 LET F3=F1-F2
2895 LET L1=33000*H*M1/F3
2905 IF L1=<T2THEN GOTO 2925
2915 LET L1=T2
2925 LET X=X+3*D/L1
2935 LET F2=169*D1*R9
2945 LET F3=F1-F2
2955 LET L1=33000*H*M1/F3
2965 IF L1=<T2THEN GOTO 2985
2975 LET L1=T2
2985 LET X=X+D/L1
2995 RETURN
```

```
* 310 D=65
* RUN
IS THIS DOZER SPOIL OR BACKFILL ? BACKFILL
IS THIS FOR LARGE OR SMALL CRATERS ? LARGE
THIS ANALYSIS IS FOR BACKFILL IN THE EVENT OF LARGE CRATERS
HOW MANY VEHICLES TO BE PROCESSED ? 16
VEH. NO.        PROD.          TOTAL TIME     DISTANCE
 1               2393.5          .658179        65
 2               2252.33         .69943         65
 3               2209.25         .713069        65
 4               2331.05         .675812        65
 5               2153.24         .731619        65
 6               2229.23         .706678        65
 7               2109.33         .746849        65
 8               1971.22         .799174        65
 9 WILL HANDLE MEAN-1 SIGMA AND LARGER
 9               4335.62         .318595        65
 10              2460.46         .640266        65
 11              2268.89         .694328        65
 12              2469.01         .63805         65
 13              3250.17         .484697        65
 14              3041.33         .517981        65
 15              2097.03         .75123         65
 16              2451.94         .642491        65

END AT 0515

*
```

```
* 2345 REM IF D<> 65 ;"D="D" THEREFORE"
* 2375 REM ;J" WILL HANDLE MEAN-1 SIGMA AND LARGER"
*  2375 REM;J" WILL HANDLE MEAN+2 AND LARGER "
* 2465 REM;J" WILL HANDLE MEAN-1 SIGMA AND LARGER"
* 2515 REM ;J" WILL HANDLE THE MEAN AND LARGER"
* 2565 REM;J" WILL HANDLE MEAN + 1 SIGMA AND LARGER"
* 265
* 275
* 247 ;"HOW MANY VEHICLES TO BE PROCESSED";
* 248 INPUT N9
* 205 GOTO 247
* 260;
* 261;
* 262;" ←THE DISTANCE IS 45 FEET THEREFORE THE VEHICLES WILL HANDLE
* 263;"THE MEAN-1 SIGN←MA AND LARGER"
* 265;
* 266;
* RUN
IS THIS DOZER SPOIL OR BACKFILL ? BACKFI;←LL
IS THIS FOR LARGE OR SMALL CRATERS ? LARGE
HOW MANY VEHICLES TO BE PROCESSED ? 16




THIS ANALYSIS IS FOR BACKFILL IN THE EVENT OF LARGE CRATERS


THE DISTANCE IS 45 FEET THEREFORE THE VEHICLES WILL HANDLE
THE MEAN-1 SIGMA AND LARGER

VEH. NO.        PROD.          TOTAL TIME     DISTANCE
 1               4697.6         .294046         45
 2               4446.1         .310679         45
 3               4316.47        .320009         45
 4               4506.49        .306516         45
 5               4259.77        .324269         45
 6               4348.28        .317668         45
 7               4142.83        .333422         45
 8               3879.82        .356024         45
 9               5253.62        .262925         45
 10              4757.41        .290349         45
 11              4403.89        .313656         45
 12              4789.21        .288421         45
 13              6078.45        .227247         45
 14              5705.16        .242116         45
 15              4114.82        .335692         45
 16              4779.73        .288993         45

END AT 0515

*
```

```
  310 D=30
* 262 ;"THE DISTANCE IS 30 FEET THEREFORE THE VEHICLES WILL HANDLE
* 263;"THE MEAN AND LARGER
* RUN
IS THIS DOZER SPOIL OR BACKFILL ? BACKFILL
IS THIS FOR LARGE OR SMALL CRATERS ? LARGE
HOW MANY VEHICLES TO BE PROCESSED ? 16
```

THIS ANALYSIS IS FOR BACKFILL IN THE EVENT OF LARGE CRATERS

THE DISTANCE IS 30 FEET THEREFORE THE VEHICLES WILL HANDLE
THE MEAN AND LARGER

VEH. NO.	PROD.	TOTAL TIME	DISTANCE
1	8636.23	.118809	30
2	8236.77	.124571	30
3	7923.22	.1295	30
4	8175.51	.125504	30
5	7920.22	.129549	30
6	7966.68	.128794	30
7	7654.03	.134055	30
8	7197.86	.142551	30
9	9698.54	.105795	30
10	8615.79	.119091	30
11	8026.54	.127833	30
12	8696.12	.11799	30
13	10570.8	9.70655E-2	30
14	9975.48	.102858	30
15	7596.83	.135064	30
16	8721.68	.117645	30

END AT 0515

*

```
  310 D=15
* 262;1←"15"
* 261 ;"THE DISTANCE IS ";
* 262;"15";
* 263;" FEET THEREFORE THE VEHICLES WILL HANDLE"
* 264;"THE MEAN+1 SIGMA AND LARGER"
* RUN
IS THIS DOZER SPOIL OR BACKFILL ? BACKFILL
IS THIS FOR LARGE OR SMALL CRATERS ? LARGE
HOW MANY VEHICLES TO BE PROCESSED ? 16




THIS ANALYSIS IS FOR BACKFILL IN THE EVENT OF LARGE CRATERS

THE DISTANCE IS 15 FEET THEREFORE THE VEHICLES WILL HANDLE
THE MEAN+1 SIGMA AND LARGER


VEH. NO.        PROD.          TOTAL TIME     DISTANCE
 1               15531          3.97843E-2     15
 2               15046.4        4.10657E-2     15
 3               14502.2        4.26067E-2     15
 4               14748.4        4.18955E-2     15
 5               14626.7        .042244        15
 6               14546.5        .042477        15
 7               14173.2        4.35956E-2     15
 8               13532.5        4.56596E-2     15
 9               17019.3        3.63052E-2     15
 10              15349          4.02561E-2     15
 11              14581.2        4.23757E-2     15
 12              15479          3.99178E-2     15
 13              17497          3.53141E-2     15
 14              16803.9        3.67706E-2     15
 15              14081.9        4.38784E-2     15
 16              15565.8        3.96953E-2     15

END AT 0515

*
```

```
  310 D=10
* 262;"10";
* 264;"THE MEAN + 2 A-SIGMA AND A-LARGER"
* RUN
IS THIS DOZER SPOIL OR BACKFILL ? BACKFILL
IS THIS FOR LARGE OR SMALL CRATERS ? LARGE
HOW MANY VEHICLES TO BE PROCESSED ? 16




THIS ANALYSIS IS FOR BACKFILL IN THE EVENT OF LARGE CRATERS

THE DISTANCE IS 10 FEET THEREFORE THE VEHICLES WILL HANDLE
THE MEAN + 2 SIGMA AND LARGER

VEH. NO.        PROD.           TOTAL TIME      DISTANCE
 1               23770.1         1.09667E-2      10
 2               23195.1         1.12386E-2      10
 3               22312.7         1.16831E-2      10
 4               22512.9         1.15791E-2      10
 5               22653.5         1.15073E-2      10
 6               22351.4         1.16628E-2      10
 7               21930.8         1.18865E-2      10
 8               21072.7         1.23705E-2      10
 9               25876.4         .010074         10
 10              23326.9         1.11751E-2      10
 11              22335.6         .011671         10
 12              23488           1.10985E-2      10
 13              25771.1         1.01152E-2      10
 14              24901.1         1.04686E-2      10
 15              21792.5         1.19619E-2      10
 16              23677.8         1.10095E-2      10

END AT 0515

*
```

```
  310 D=5
* 262;"5";
* RUN
IS THIS DOZER SPOIL OR BACKFILL ? BACKFILL
IS THIS FOR LARGE OR SMALL CRATERS ? LARGE
HOW MANY VEHICLES TO BE PROCESSED ? 16



THIS ANALYSIS IS FOR BACKFILL IN THE EVENT OF LARGE CRATERS

THE DISTANCE IS 5 FEET THEREFORE THE VEHICLES WILL HANDLE
 THE MEAN + 2 SIGMA AND LARGER

VEH. NO.        PROD.          TOTAL TIME     DISTANCE
 1               25682.7        .01015          5
 2               25343.3        .010286         5
 3               24807.3        1.05082E-2      5
 4               24930.6        1.04562E-2      5
 5               25016.5        1.04203E-2      5
 6               24831.2        1.04981E-2      5
 7               24569.5        1.06099E-2      5
 8               24021.6        1.08519E-2      5
 9               26864          9.70369E-3      5
 10              25421.8        1.02542E-2      5
 11              24821.5        1.05022E-2      5
 12              25517.1        1.02159E-2      5
 13              26807.2        9.72427E-3      5
 14              26328.7        9.90098E-3      5
 15              24482.4        1.06476E-2      5
 16              25628.7        1.01714E-2      5

END AT 0515

*
```

```
  310 D=15
* 262;"15";
* RUN
IS THIS DOZER SPOIL OR BACKFILL ? BACKFILL
IS THIS FOR LARGE OR SMALL CRATERS ? SMALL
HOW MANY VEHICLES TO BE PROCESSED ? 16




THIS ANALYSIS IS FOR BACKFILL IN THE EVENT OF SMALL CRATERS

THE DISTANCE IS 15 FEET THEREFORE THE VEHICLES WILL HANDLE
THE ENTIRE POPULATION


VEH. NO.        PROD.          TOTAL TIME     DISTANCE
 1               1169.35        .157139        15
 2               1138.61        .161381        15
 3               1138.78        .161357        15
 4               1170.71        .156956        15
 5               1117.27        .164463        15
 6               1144.06        .160612        15
 7               1114.26        .164907        15
 8               1082.62        .169728        15
 9               1205.99        .152364        15
 10              1193.3         .153984        15
 11              1155.8         .158981        15
 12              1192.07        .154143        15
 13              1330.3         .138127        15
 14              1303.1         .14101         15
 15              1112.49        .165171        15
 16              1185.08        .155053        15

END AT 0515

*
```

```
  310 D=60
* 262 ;"60";
* 264 ;"V←THE ENTIRE POPULATION"
* RUN
IS THIS DOZER SPOIL OR BACKFILL ? SPOIL
IS THIS FOR A LARGE OR A SMALL CRATER ? LARGE
HOW MANY VEHICLES TO BE PROCESSED ? 16




THIS ANALYSIS IS FOR SPOIL IN THE EVENT OF LARGE CRATERS

THE DISTANCE IS 60 FEET THEREFORE THE VEHICLES WILL HANDLE
 THE ENTIRE POPULATION


VEH. NO.       PROD.          TOTAL TIME     DISTANCE
 1              2516.39        .626037         60
 2              2372.1         .664115         60
 3              2327.97        .676704         60
 4              2452.62        .642313         60
 5              2270.52        .693828         60
 6              2348.45        .670805         60
 7              2225.43        .707886         60
 8              2083.28        .756187         60
 9              2648.19        .563608         60
 10             2584.65        .609502         60
 11             2389.05        .659405         60
 12             2593.35        .607457         60
 13             3381.3         .4659           60
 14             3172.12        .496623         60
 15             2212.79        .711931         60
 16             2575.97        .611555         60

END AT 0515

*
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```
* 264;"THE MEAN ; ←←+ 2 SIGMA
* 1895 REM;J" CAN HANDLE MEAN+2 SIGMA"
* 2095REM IFD<>60 ;"D="D" THEREFORE ";
* RUN
IS THIS DOZER SPOIL OR BACKFILL ? SPOIL
IS THIS FOR A LARGE OR A SMALL CRATER ? LARGE
HOW MANY VEHICLES TO BE PROCESSED ? 16
```

THIS ANALYSIS IS FOR SPOIL IN THE EVENT OF LARGE CRATERS

THE DISTANCE IS 55 FEET THEREFORE THE VEHICLES WILL HANDLE THE MEAN + 2 SIGMA

VEH. NO.	PROD.	TOTAL TIME	DISTANCE
1	2530.87	.589735	55
2	2390.92	.624254	55
3	2350.43	.635007	55
4	2472.87	.603567	55
5	2292.39	.651084	55
6	2370.55	.629618	55
7	2250.14	.663309	55
8	2111.58	.706836	55
9	2782.13	.536474	55
10	2599.62	.574138	55
11	2410.76	.619117	55
12	2608.23	.572242	55
13	3361.39	.444024	55
14	3164.67	.471626	55
15	2238.06	.666889	55
16	2590.3	.576204	55

END AT 0515

*

```
  310 D=50
* 262;"50"
* 264;"THE MEAN+1 SIGMA
* 1945 REM;J" CAN HANDLE THE MEAN+1 SIGMA"
* RUN
IS THIS DOZER SPOIL OR BACKFILL ? SPOIL
IS THIS FOR A LARGE OR A SMALL CRATER ? LARGE
HOW MANY VEHICLES TO BE PROCESSED ? 16


THIS ANALYSIS IS FOR SPOIL IN THE EVENT OF LARGE CRATERS

THE DISTANCE IS 50
 FEET THEREFORE THE VEHICLES WILL HANDLE

STOP AT 0263

* 262;"50";
* RUN
IS THIS DOZER SPOIL OR BACKFILL ? SPOIL
IS THIS FOR A LARGE OR A SMALL CRATER ? LARGE
HOW MANY VEHICLES TO BE PROCESSED ? 16




THIS ANALYSIS IS FOR SPOIL IN THE EVENT OF LARGE CRATERS

THE DISTANCE IS 50 FEET THEREFORE THE VEHICLES WILL HANDLE
THE MEAN+1 SIGMA

VEH. NO.      PROD.         TOTAL TIME    DISTANCE
 1             2415.55       .544252        50
 2             2287.87       .574625        50
 3             2255.42       .582894        50
 4             2369.82       .554754        50
 5             2198.29       .598042        50
 6             2274.2        .578079        50
 7             2162.78       .607862        50
 8             2036.06       .645692        50
 9             2634.84       .498957        50
 10            2483.17       .529432        50
 11            2312.37       .568538        50
 12            2489.38       .528111        50
 13            3167.4        .415063        50
 14            2995.38       .438898        50
 15            2152.18       .610855        50
 16            2471.32       .531971        50

END AT 0515

*
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```
  310 D=35
* 262;"35";
* 264;"THE MEAN CHUNK SIZE"
* 1995 REM;J"WILL HANDLE THE MEAN CHUNK SIZE"
* RUN
IS THIS DOZER SPOIL OR BACKFILL ? SPOIL
IS THIS FOR A LARGE OR A SMALL CRATER ? LARGE
HOW MANY VEHICLES TO BE PROCESSED ? 16




THIS ANALYSIS IS FOR SPOIL IN THE EVENT OF LARGE CRATERS

THE DISTANCE IS 35 FEET THEREFORE THE VEHICLES WILL HANDLE
THE MEAN CHUNK SIZE

VEH. NO.        PROD.           TOTAL TIME     DISTANCE
 1               2318.63         .412941         35
 2               2215.5          .432164         35
 3               2196.45         .435912         35
 4               2293.26         .41751          35
 5               2143.18         .446747         35
 6               2212.38         .432773         35
 7               2119.24         .451794         35
 8               2015.06         .475153         35
 9               2479            .386228         35
 10              2380.59         .402195         35
 11              2245.66         .42636          35
 12              2382.98         .401791         35
 13              2901.75         .329959         35
 14              2779.42         .344482         35
 15              2111.3          .453493         35
 16              2365.84         .404702         35

END AT 0515

*
```

```
 310 D=20
* 262;"20";
* 264;"THE MEAN-1SIGMA
* 264;"THE MEAN-1 SIGMA
* 1805REM ;J" CAN HANDLE THE MEAN-1 SIGMA"
* RUN
IS THIS DOZER SPOIL OR BACKFILL ? SPOIL
IS THIS FOR A LARGE OR A SMALL CRATER ? LARGE
HOW MANY VEHICLES TO BE PROCESSED ? 16




THIS ANALYSIS IS FOR SPOIL IN THE EVENT OF LARGE CRATERS

THE DISTANCE IS 20 FEET THEREFORE THE VEHICLES WILL HANDLE
 THE MEAN-1 SIGMA

VEH. NO.        PROD.        TOTAL TIME     DISTANCE
 1              2062.19      .266362         20
 2              1995.87      .275213         20
 3              1989.29      .276124         20
 4              2054.77      .267324         20
 5              1949.23      .281799         20
 6              2000.12      .274628         20
 7              1937.66      .283481         20
 8              1868.86      .293917         20
 9              2152.95      .255134         20
 10             2107.28      .260662         20
 11             2023.4       .271468         20
 12             2106.87      .260714         20
 13             2414.69      .227479         20
 14             2348.82      .233858         20
 15             1933.06      .284156         20
 16             2094.04      .262311         20

END AT 0515

*
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```
  310 D=40
* 262;"40";
* RUN
IS THIS DOZER SPOIL OR BACKFILL ? SPOIL
IS THIS FOR A LARGE OR A SMALL CRATER ? SMALL
HOW MANY VEHICLES TO BE PROCESSED ? 16



THIS ANALYSIS IS FOR SPOIL IN THE EVENT OF SMALL CRATERS

THE DISTANCE IS 40 FEET THEREFORE THE VEHICLES WILL HANDLE
THE ENTIRE POPULATION

VEH. NO.        PROD.           TOTAL TIME     DISTANCE
 1               777.745         .23626          40
 2               742.211         .247571         40
 3               742.404         .247507         40
 4               779.356         .235771         40
 5               718.361         .25579          40
 6               748.412         .24552          40
 7               715.049         .256975         40
 8               680.985         .26983          40
 9               822.05          .223527         40
 10              806.464         .227847         40
 11              761.905         .241172         40
 12              804.967         .22827          40
 13              990.24          .185561         40
 14              950.846         .193249         40
 15              713.102         .257677         40
 16              796.5           .230697         40

END AT 0515

*
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```
3000 REM THIS IS THE TRUCK TEAM HAULING PROGRAM
3002 PRINT "HOW MANY TEAMS TO BE EVALUATED";
3003 INPUT S9
3004 PRINT "                         TRUCK HAULING PROGRAM"
3005 PRINT
3006 PRINT "TEAM NO.","PRODUCTIVITY","    T0"
3007 PRINT
3008 FOR Y=1TO S9
3100   READ H,M1,W3,V,N,G,R0,B,B1
3110   READ W,D,T4,T5,C,P1,R,G1,V3,V4,E,Q1,Q2,N1,F
3120   IF V*R0=<W3THEN GOTO 3130
3125   LET V=W3/R0
3130   LET L1=V/B
3140   IF L1>1THEN GOTO 3150
3145   LET L1=1
3150   LET L1=L1
3155   LET V=L1*B
3156   IF L1-INT(L1)=0THEN GOTO 3160
3158   LET L1=INT(L1)+1
3159   REM ALLOWS CYC TIME TO FULL LOAD USING PART BUCKET LOAD
3160   LET T1=L1*B1
3170   LET F1=N*G*C+W*TAN(P1)
3180   LET F2=W*(R+SIN(G1))
3190   LET F3=V*R0*(R+SIN(G1))
3200   LET F4=N*G*C+((W+V*R0)*TAN(P1))
3210   LET F5=F4-(F2+F3)
3220   LET A=33000*H*M1
3230   LET V2=A/(F2+F3)
3240   IF V2=>V3THEN GOTO 3280
3250   GOTO 3290
3280   LET V2=V3
3290   LET M2=W/115920+V*R0/115920
3295   LET V1=A/F5
3300   LET F6=A*(1+LOG(V2/V1))/V2
3305   LET F7=.1*(F6-(F2+F3))
3310   LET K1=F7/M2
3320   LET T2=V2/K1
3330   LET X2=.5*K1*T2↑2
3340   LET T3=(D-X2)/V2
3350   LET V5=A/F2
3360   IF V5=>V4THEN GOTO 3390
3370   GOTO 3400
3390   LET V5=V4
3400   LET M3=W/115920
3410   LET F8=A*(1+LOG(V5/V1))/V5
3415   LET F9=.1*(F8-F2)
3420   LET K2=F9/M3
3430   LET T6=V5/K2
3440   LET X3=.5*K2*T6↑2
3450   LET T7=(D-X3)/V5
3460   LET T8=T1+T2+T3+T4+T5+T6+T7
3470   LET W2=F/V
3480   LET P=V*60*E/T8
```

```
3490    LET T9=T8+Q1+Q2
3500    LET T0=W2/N1*T9
3510    PRINT Y,P,T0
3600    DATA 197,.8,12000,108,4,.48,109,94.5,.4,13660,4400
3605    DATA .5,1,1,.805,.02,.01,1760,3080,.7,0,0,5,2160
3610    DATA 200,.8,24000,216,8,.56,109,94.5,.4,23000,4400
3615    DATA .5,1,1,.805,.02,.01,1760,3080,.7,0,0,5,2160
4000 NEXT Y
4010 END
```

```
                    TRUCK HAULING PROGRAM

TEAM NO.        PRODUCTIVITY        T0

 1                670.768         27.0496
 2                1218.87         14.8859

END AT 4010

*
```

TRUCK TEAM HAULING PROGRAM SYMBOL TABLE

SYMBOL	VALUE
H	HORSEPOWER
M1	MECHANICAL EFFICIENCY
W3	TON RATING
V	PAYLOAD VOLUME
G	GCA
R0	LOOSE DENSITY
B	BUCKET VOLUME
B1	LOADER CYCLE TIME
W	TRUCK EMPTY
D	DISTANCE
T4	FIXED TIME
T5	FIXED TIME
C	SOIL COHESION
P1	SOIL SHEAR ANGLE
R	ROLLING RESISTANCE
G1	HAUL GRADE
V3	MAXIMUM HAUL VELOCITY
V4	MAXIMUM RETURN VELOCITY
E	JOB EFFICIENCY
Q1	QUEUE TIME
Q2	QUEUE TIME
N1	NUMBER OF TRUCKS
F	FILL VOLUME
N	NUMBER OF WHEELS DRIVEN

TABLE D-1 DOZER CHARACTERISTICS

Identification	Type	HP	Weight	Turning Circle	Blade Size	Tire - Track Size	Max Velocity	Size: Length with Blade	Size: Width w/o Blade	Size: Height
Caterpillar 814	Rubber tired	170	36,000 lb.	17.3 ft.	12 ft.	23.5 x 25	19.8 mph	255 in	109 in	134 in
Caterpillar 824B		300	62,400	23.4	13.25	29.5 x 29	18.5	291	121	143
Caterpillar 834S		400	76,000	25.2	14.67	29.5 x 35	20.4	305	130	146
Clark 280		301	69,700	22.1	13.33	29.5 x 29	28.8	327	132	154
Clark 380		472	116,000	24.6	16.33	33.25 x 35	20.3	396	141	174
Steiger Bearcat		210	23,000	16	12	30.5 x 32	20.9	264	103	130
Steiger Tiger	Rubber tired	272	32,000	16.5	12	30.5 x 32	17.6	280	103	137
Caterpillar D7F	Crawler	180	44,600	18.7	11.33	107in x 20in	5.9	225	101	120
Caterpillar D8K		300	69,950	21.7	12	115in x 22in	6.7	261	107	122
International Harvester TD-20E		210	39,950	19.3	11.1	108.5in x 22in	6.4	232	100	127
Terex 82-20	Crawler	180	36,855	18.5	10.75	107in x 20in	7.0	222	98	111

TABLE D-2 LOADER CHARACTERISTICS (1)

Identification	HP	Weight lbs.	Turning Circle	Range of Bucket Sizes	Breakout Force	Tipping Load at Max Articulation	Tire Size	Max Velocity	Size: Length	Size: Width	Size: Height
Case W26B	165	33,045(2)	472 in.	2.5-5 cu.yd.	27,100	10,305	23.5 x 25	29.9 mph	296(3)	87	206 (3)
Eaton Yale 1700	104	18,045	230	1.75-2.5	20,300	12,163	14.00 x 24	18.2	251.5	90.5	125.5
International Harvester 560	380	79,210	316	6.5-12	64,181	46,986	29.5 x 29	22.2	353	133	158.5
Eaton Yale 4000	260	46,500	269	4-5	38,240	32,731	26.5 x 25	21.2	325	126	138
Terex 72-71	336	76,250	568	6.5-7	65,800	44,900	29.5 x 29	20.8	386	107	162

Notes: (1) All loaders are articulated frame, rubber-tired types.
(2) Includes tire ballast
(3) Bucket on ground dimension

TABLE D-3. Typical Truck Characteristics

Size	Gross Vehicle Weight Rating	Front Axle Rating	Rear Axle Rating	HP	Chasis Weight	Turning Radius	Dimensions Length	Width	Height
5-ton	23,660 pounds	7,500 pounds	16,160 pounds	195	5,800 pounds	25 ft 8 in.	234 in.	90 in.	87 in.
10-ton	43,000 pounds	12,000 pounds	31,000 pounds	210	11,800 pounds	28 ft 3 in.	270 in.	95.5 in.	96.3 in.

TABLE D-4. Rubber-Tired Excavator Characteristics

Identification	Weight	Maximum Digging Depth	Lifting Capacity at 25-foot radius(1)	Swings per minute	Size (ft) Length(2)	Width	Height(2)	HP
Bantam S-155	32,200 pounds	19 feet	5140 pounds	6.5	33.75	8	12.67	136
Drott 40BYR	34,720 pounds	18.75	4750	6	29.83	8	13	117
Poclain 115-P	41,800 pounds	21.33	11,000	Not Available		9		148

Notes: (1) Over end reach
(2) Travel dimension

TABLE D-5. Compactor Characteristics

Identification	Type	HP	Weight Bare	Weight Ballasted	Vibrator Frequency	Total Force	Tool Size	Turning Circle	Size Length	Width	Height
RayGo Rascal 400-A	Vibratory Drum	88	20,000 lbs	20,355 lbs	1,100-1,500 vib/min	38,000 lbs	84in. long	20.4ft	17.3	8	8.4
Tampo SP-950	Rubber Tired	130	20,200	37,654	N/A	6,000 lbs/ wheel max	9 tires, 11x20 90in. rolling width	25.5ft	16.1	7.5	9.3
Military Vibr Roller(1)	Towed Vibratory	N/A	10,000	N/A	UNK.	14,000lbs (est)	60 in. long	40ft	6	7	5

(1) Characteristics approximated from film observations and comparison to commercial equipment

TABLE D-6. Grader Characteristics

Identification	HP	Size (ft) Length	Width	Height (2)	Wheelbase	Blade Width	Weight	Turning Radius (ft)
Caterpillar 12G	135	27.3	7.75	10.9	263 in.	12 ft	27,800 lbs	24
Galion T-400	125	25.9	8	10.8	230 in.	12 ft	24,300 lbs	36
Wabco 444	125	26.3	7.75	10.7	230 in.	12 ft	25,220 lbs	40

(2) Height with cab, or R.O.P.

TABLE D-7 EQUIPMENT LISTS

(3 CRATER TEAM)

		Quantity		
Equipment	Make	Mix A	Mix B	Mix C
Crawler	TD-20	3*	3	3
o Ripper				
Loader	(Military) AC645	7	-	-
o 2 1/2 cy Bucket	compares to Yale 1700	7	-	-
o Forks		3	-	-
Loader	Yale 1700		7	9
o 3 1/2 cy Bucket		-	7	9
o Forks		-	3	3
5-Ton Truck	International Loadstar 1700	15	-	-
10-Ton Truck	International Fleetstar F-2010A	-	15	15
Grader	Caterpillar 12G	3	3	3
R-T Dozer	Steiger Bearcat	-	-	3
Excavator	Poclain115-P	-	-	3
Vib. Compactor	(≈ Bros VP4D)	3	3	-
Tractor	(Price a 75 HP Ford)	3	3	-
S/P Vib. Compactor	RayGo Rascal 400A	-	-	3
RT Comp. (S/P)	Tampo SP-950	-	-	3
Rotary Broom		2	2	-
Vacuum		2	2	-
Wet Brush		-	-	3
Jeep	(Tows Broom)	2	2	-

* Except in UK Small Crater, Replaced by Excavator to Allow Digging out Crater.

TABLE D-7 EQUIPMENT LISTS

(3 CRATER TEAM)

Equipment	Make	Quantity Mix A	Mix B	Mix C
Crawler	TD-20	3*	3	3
o Ripper				
Loader	(Military) AC645	7	-	-
o 2 1/2 cy Bucket	compares to Yale 1700	7	-	-
o Forks		3	-	-
Loader	Yale 1700		7	9
o 3 1/2 cy Bucket		-	7	9
o Forks		-	3	3
5-Ton Truck	International Loadstar 1700	15	-	-
10-Ton Truck	International Fleetstar F-2010A	-	15	15
Grader	Caterpillar 12G	3	3	3
R-T Dozer	Steiger Bearcat	-	-	3
Excavator	Poclain115-P	-	-	3
Vib. Compactor	(≈ Bros VP4D)	3	3	-
Tractor	(Price a 75 HP Ford)	3	3	-
S/P Vib. Compactor	RayGo Rascal 400A	-	-	3
RT Comp. (S/P)	Tampo SP-950	-	-	3
Rotary Broom		2	2	-
Vacuum		2	2	-
Wet Brush		-	-	3
Jeep	(Tows Broom)	2	2	-

* Except in UK Small Crater, Replaced by Excavator to Allow Digging out Crater.